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Handout in Support of the Subject of Shipborne Navigational Aids including Gyrocompass, Echosounder, Speedlog and Magnetic Compass

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Contents

Chapter 1 The Ship's Gyrocompass 1
1.1 Introduction 1
1.2 Gyroscopic principles 1
1.3 The controlled gyroscope 6
1.4 The north-seeking gyro 7
1.5 A practical gyrocompass 15
1.6 Follow-up systems 17
1.7 Compass errors 18
1.8 Top-heavy control master compass 22
1.9 A digital controlled top-heavy gyrocompass system 28
1.10 A bottom-heavy control gyrocompass 34
1.11 Starting a gyrocompass 42
1.12 Compass repeaters 42
1.13 Glossary 46
1.14 Summary 47
1.15 Revision questions 47
Chapter 2 The Ship's Echosounder 48
2.1 Introduction 48
2.2 The characteristics of sound in seawater 48
2.3 Transducers 53
2.4 Depth sounding principles 57
2.5 A generic echo sounding system 60
2.6 A digitized echo sounding system 63
2.7 A microcomputer echo sounding system 66
2.8 Glossary 70
2.9 Summary 70
2.10 Revision questions 71
Chapter 3 The Ship's Speed Log 72
3.1 Introduction 72
3.2 Speed measurement using water pressure 72
3.3 Speed measurement using electromagnetic induction 79
3.4 Speed measurement using acoustic correlation techniques 85
3.5 The Doppler principle 89
3.6 Principles of speed measurement using the Doppler effect 90
3.7 The Furono Doppler Sonar DS-50 System 99
3.8 Glossary 102
3.9 Summary 103
3.10 Revision questions 104

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Chapter 4 The Ship's Magnetic Compass.....105
4.1 Introduction.....105
4.2 Magnetism.....114
4.3 Theory of magnetic compass adjustment.....117
4.4 Glossary.....125
4.5 Revision questions.....125
References.....126

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Chapter 1 The Ship's Gyrocompass

1.1 Introduction

Of all the navigation instruments in use today, the master compass is the oldest and probably the one that most navigators feel happiest with. However, even the humble compass has not escaped the advance of microelectronics. Although modern gyrocompasses are computerized the principles upon which they work remain unchanged.

1.2 Gyroscopic principles

At the heart of a marine gyrocompass assembly is a modern gyroscope consisting of a perfectly balanced wheel arranged to spin symmetrically at high speed about an axis or axle. The wheel, or rotor, spins about its own axis and, by suspending the mass in a precisely designed gimbals assembly, the unit is free to move in two planes each at right angles to the plane of spin. There are therefore three axes in which the gyroscope is free to move as illustrated in Figure 1.1:

- the spin axis
- the horizontal axis
- the vertical axis.

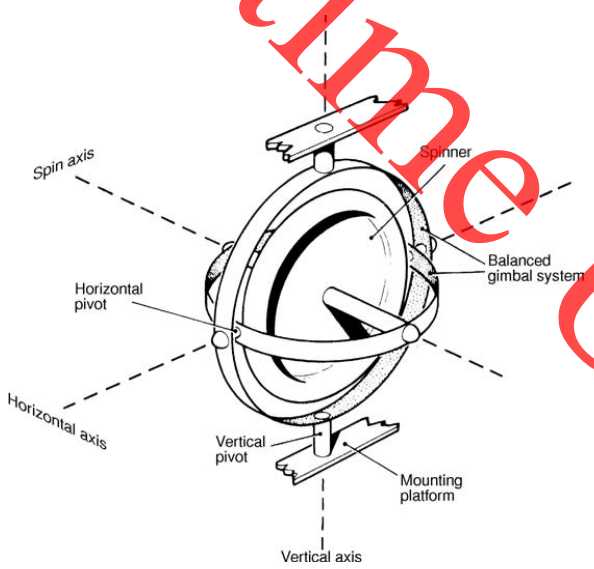

Figure 1.1 A free gyroscope. (Reproduced courtesy of S. G. Brown Ltd.)

In a free gyroscope none of the three freedoms is restricted in any way. Such a gyroscope is almost universally used in the construction of marine gyrocompass mechanisms. Two other types of gyroscope, the constrained and the spring-restrained are now rarely seen.

In order to understand the basic operation of a free gyroscope, reference must be made to some of the first principles of physics. A free gyroscope possesses certain inherent properties, one of which is inertia, a phenomenon that can be directly related to one of the basic laws of motion documented by Sir

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Isaac Newton. Newton's first law of motion states that 'a body will remain in its state of rest or uniform motion in a straight line unless a force is applied to change that state'. Therefore a spinning mass will remain in its plane of rotation unless acted upon by an external force. Consequently the spinning mass offers opposition to an external force. This is called 'gyroscopic inertia'. A gyroscope rotor maintains the direction of its plane of rotation unless an external force of sufficient amplitude to overcome inertia is applied to alter that direction. In addition a rapidly spinning free gyroscope will maintain its position in free space irrespective of any movement of its supporting gimbals (see Figure 1.2).

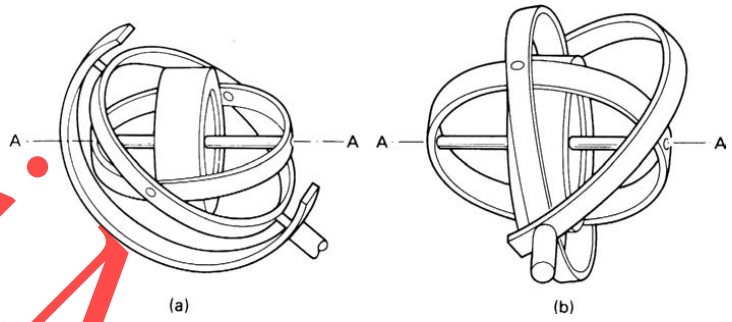

Figure 1.2 The gyrospin axis is stabilized irrespective of any movement of the supporting gimbals. (Reproduced courtesy of Sperry Ltd.)

Also from the laws of physics it is known that the linear momentum of a body in motion is the product of its mass and velocity (mv). In the case of a freely spinning wheel (Figure 1.3), it is more convenient to think in terms of angular momentum.

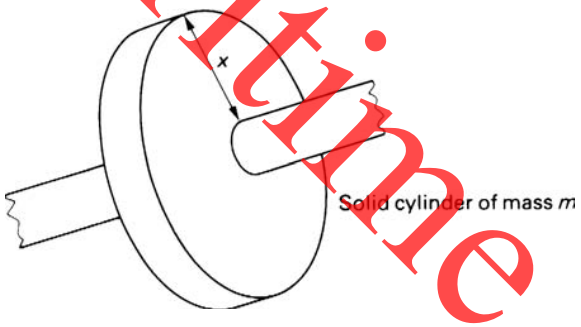

Figure 1.3 A spinning rotor possessing a solid mass.

The angular momentum of a particle spinning about an axis is the product of its linear momentum and the perpendicular distance of the particle from the axle:

$$\text{angular momentum} = mv \cdot r$$

where r = rotor radius.

The velocity of the spinning rotor must be converted to angular velocity (ω) by dividing the linear tangential velocity (v) by the radius (r). The angular momentum for any particle spinning about an axis is now:

$$m\omega r^2$$

For a spinning rotor of constant mass where all the rotating particles are the same and are concentrated at the outer edge of the rotor, the angular momentum is the product of the moment of inertia (I) and the angular velocity:

$$\text{angular momentum} = I\omega$$

where $I = 0.5\ mr^2$.

It can now be stated that gyroscopic inertia depends upon the momentum of the spinning rotor. The

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momentum of such a rotor depends upon three main factors:

- the total mass, M of the rotor (for all particles)
- the radius r summed as the constant K (for all the particles) where K is the radius of gyration
- the angular velocity ω.

The angular momentum is now proportional to ωMK^2. If one or more of these factors is changed, the rotor's gyroscopic inertia will be affected. In order to maintain momentum, a rotor is made to have a large mass, the majority of which is concentrated at its outer edge. Normally the rotor will also possess a large radius and will be spinning very fast. To spin freely the rotor must be perfectly balanced (its centre of gravity will be at the intersection of the three axes) and its mounting bearings must be as friction-free as possible. Once a rotor has been constructed, both its mass and radius will remain constant. To maintain gyroscopic inertia therefore it is necessary to control the speed of the rotor accurately. This is achieved by the use of a precisely controlled servo system.

1.2.1 Precession

Precession is the term used to describe the movement of the axle of a gyroscope under the influence of an external force. If a force is applied to the rotor by moving one end of its axle, the gyroscope will be displaced at an angle of 90° from the applied force. Assume that a force is applied to the rotor in Figure 1.4 by lifting one end of its axle so that point A on the rotor circumference is pushed downwards into the paper. The rotor is rapidly spinning clockwise, producing gyroscopic inertia restricting the effective force attempting to move the rotor into the paper.

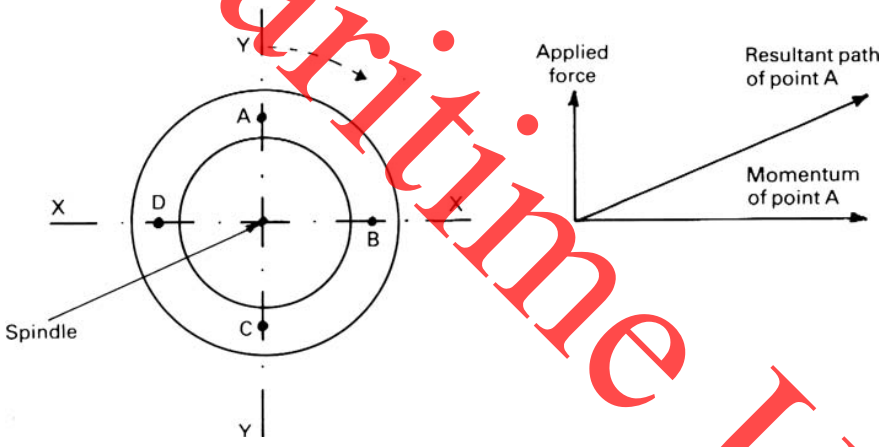

Figure 1.4 Gyro precession shown as a vector sum of the applied forces and the momentum.

As the disturbing force is applied to the axle, point A continues its clockwise rotation but will also move towards the paper. Point A will therefore move along a path that is the vector sum of its original gyroscopic momentum and the applied disturbing force. As point A continues on its circular path and moves deeper into the paper, point C undergoes a reciprocal action and moves away from the paper. The plane of rotation of the rotor has therefore moved about the H axis although the applied force was to the V axis. The angular rate of precession is directly proportional to the applied force and is inversely proportional to the angular momentum of the rotor. Figure 1.5 illustrates the rule of gyroscopic precession.

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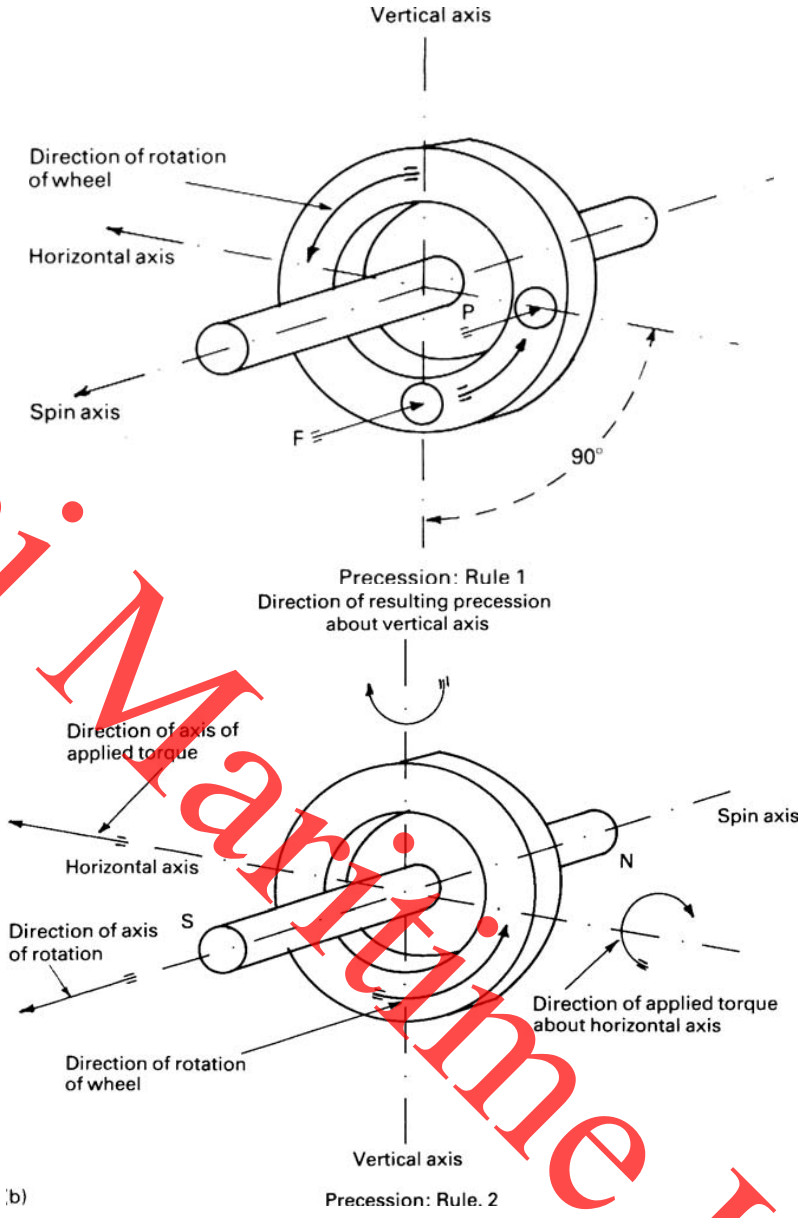

Figure 1.5 (a) Resulting precession P occurs at 90° in the direction of spin from the applied force F. This direction of precession is the same as that of the applied force. (Reproduced courtesy of Sperry Ltd.) (b) The direction of axis rotation will attempt to align itself with the direction of the axis of the applied torque. (Reproduced courtesy of Sperry Ltd.)

1.2.2 The free gyroscope in a terrestrial plane

Now consider the case of a free gyroscope perfectly mounted in gimbals to permit freedom of movement on the XX and YY axes. In this description, the effect of gravity is initially ignored. It should be noted that the earth rotates from west to east at a rate of 15°/h and completes one revolution in a 'sidereal day' which is equivalent to 23 h 56 min 4 s. The effect of the earth's rotation beneath the gyroscope causes an apparent movement of the mechanism. This is because the spin axis of the free gyroscope is fixed by inertia to a celestial reference (star point) and not to a terrestrial reference point.

If the free gyro is sitting at the North Pole, with its spin axis horizontal to the earth's surface, an apparent clockwise movement of the gyro occurs. The spin axis remains constant but as the earth rotates in an anticlockwise direction (viewed from the North Pole) beneath it, the gyro appears to rotate clockwise at a rate of one revolution for each sidereal day (see Figure 1.6).

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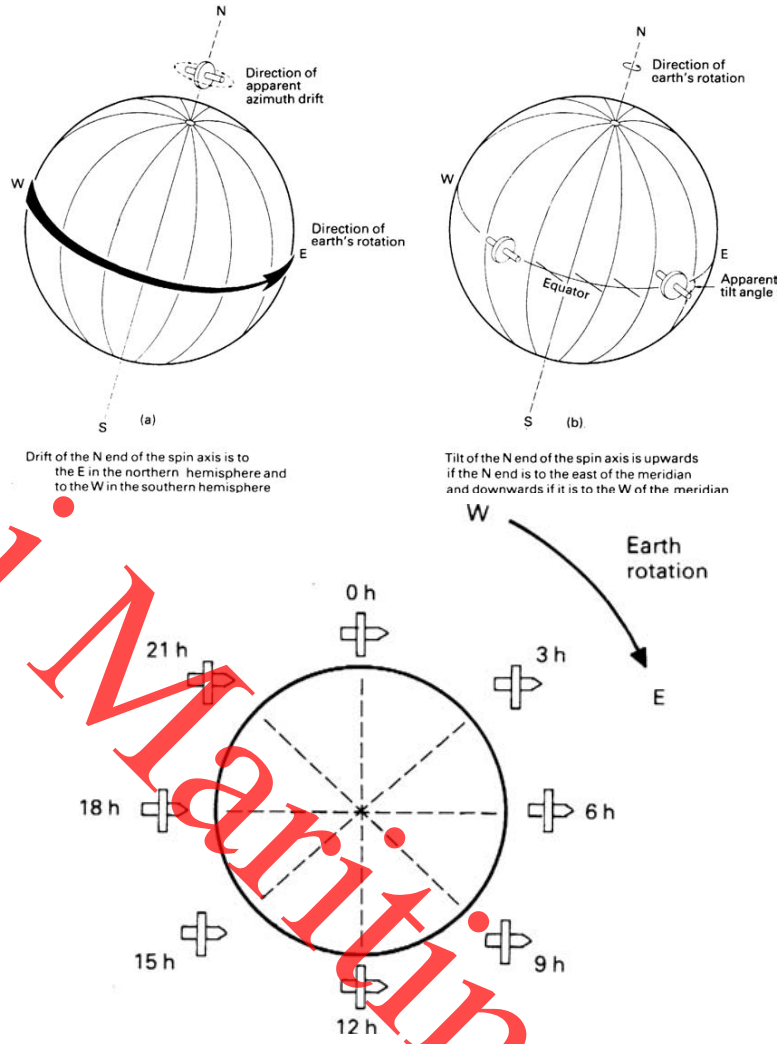

Figure 1.6 (a) Effect of earth rotation on the gyro. (Reproduced courtesy of Sperry Ltd.) (b)View from the South Pole. The earth rotates once every 24 h carrying the gyro with it. Gyroscopic inertia causes the gyro to maintain its plane of rotation with respect to the celestial reference point. However, in relation to the surface of the earth the gyro will tilt.

The reciprocal effect will occur at the South Pole. This phenomenon is known as gyro drift. Drift of the north end of the spin axis is to the east in the northern hemisphere and to the west in the southern hemisphere. There will be no vertical or tilting movement of the spin axis. Maximum gyro tilt occurs if the mechanism is placed with its spin axis horizontal to the equator. The spin axis will be stabilized in line with a star point because of inertia. As the earth rotates the eastern end of the spin axis appears to tilt upwards. Tilt of the north end of the spin axis is upwards if the north end is to the east of the meridian and downwards if it is to the west of the meridian. The gyro will appear to execute one complete revolution about the horizontal axis for each sidereal day. No drift in azimuth occurs when the gyro is directly over the equator. The relationship between drift and tilt can be shown graphically (see Figure 1.7).

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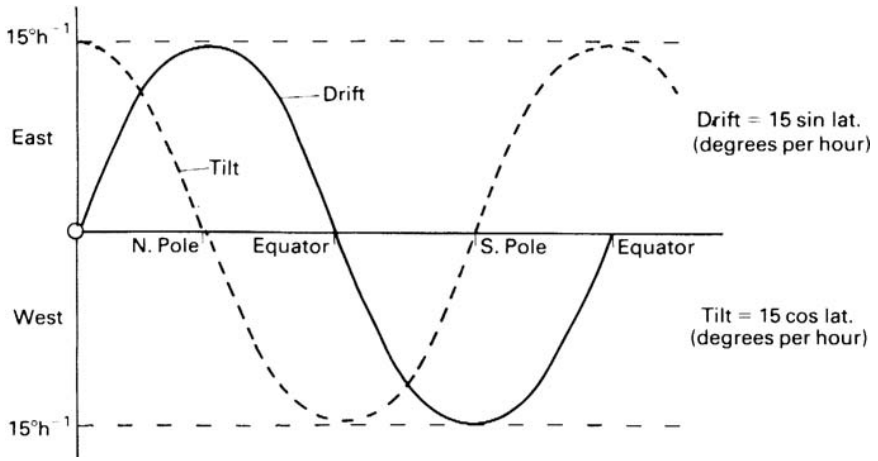

Figure 1.7 The graphical relationship between drift and tilt.

Figure 1.7 shows that gyro drift will be maximum at the poles and zero at the equator, whilst gyro tilt is the reciprocal of this. At any intermediate latitude the gyro will suffer from both drift and tilt with the magnitude of each error being proportional to the sine and cosine of the latitude, respectively.

When a gyro is placed exactly with its spin axis parallel to the spin axis of the earth at any latitude, the mechanism will maintain its direction relative to the earth. There is no tilt or azimuth movement and the gyro may be considered to be Meridian stabilized. As the earth rotates the gyro will experience a movement under the influence of both tilt and azimuth motion. The rate of tilt motion is given as:

tilt = 15° cos latitude (degrees per hour)

where 15° is the hourly rate of the earth's rotation. The azimuth drift is:

azimuth drift = 15° sin latitude (degrees per hour)

1.2.3 Movement over the earth's surface

The free gyroscope, as detailed so far, is of no practical use for navigation since its rotor axis is influenced by the earth's rotation and its movement over the earth's surface. The stabilized gyroscopic change in position of longitude along a parallel of latitude requires a correction for the earth's rotary motion. Movement in latitude along a meridian of longitude involves rotation about an axis through the centre of the earth at right angles to its spin axis. Movement of the mechanism in any direction is simply a combination of the latitudinal and longitudinal motions. The faster the gyroscope moves the greater the rate of angular movement of the rotor axle attributable to these factors.

1.3 The controlled gyroscope

It has been stated that a free gyroscope suffers an apparent movement in both azimuth and tilt of the rotor axis depending upon its latitudinal location. When fitted to a vessel the latitude is known and consequently the extent of movement in azimuth and tilt is also known. It is possible therefore to calculate the necessary force required to produce a reciprocal action to correct the effect of apparent movement. A force can be applied to the gyro that will cause both azimuth and tilt precession to occur in opposition to the unwanted force caused by the gyro's position on the earth. The amplitude of the reciprocal force must be exactly that of the force producing the unwanted movement, otherwise over or under correction will occur. If the negative feedback is correctly applied, the gyro will no longer seek a celestial point but will be terrestrially stabilized and will assume a fixed attitude.

If the gyro is drifting in azimuth at '*N*' degrees per hour in an anticlockwise direction, an upward force sufficient to cause clockwise precession at a rate of '–*N*' degrees per hour must be applied vertically to

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the appropriate end of the rotor axle. The result will be that the gyro drift is cancelled and the instrument points to a fixed point on earth. Gyro tilt movement can also be cancelled in a similar way by applying an equal and opposite force horizontally to the appropriate end of the rotor axle.

Although the gyro is now stabilized to a terrestrial point it is not suitable for use as a navigating compass for the following reasons.

It is not north-seeking. Since the recognized compass datum is north, this factor is the prime reason why such a gyro is not of use for navigation.

- It is liable to be unstable and will drift if the applied reciprocal forces are not precise.
- A complex system of different reciprocal forces needs to be applied due to continual changes in latitude.
- Because of precessional forces acting upon it through the friction of the gimbal bearings, the mechanism is liable to drift. This effect is not constant and is therefore difficult to compensate for.

1.4 The north-seeking gyro

The gyrospin axis can be made meridian-seeking (maintaining the spin axis parallel to the earth's spin axis) by the use of a pendulum acting under the influence of earth gravity. The pendulum causes a force to act upon the gyro assembly causing it to precess. Precession, the second fundamental property of a gyroscope, enables the instrument to become north-seeking. As the pendulum swings towards the centre of gravity, a downward force is applied to the wheel axle, which causes horizontal precession to occur. This gravitational force acting downward on the spinner axle causes the compass to precess horizontally and maintain the axle pointing towards true north.

The two main ways of achieving precessional action due to gravity are to make the gyro spin axis either bottom or top heavy. Bottom-heavy control and a clockwise rotating gyro spinner are used by some manufacturers, whereas others favour a top-heavy system with an anticlockwise rotating spinner. Figure 1.8(a) illustrates this phenomenon.

With bottom-heavy control, tilting upwards of the south end produces a downward force on the other end, which, for this direction of spinner rotation, produces a precession of the north end to the west. In a top-heavy control system, tilting upwards of the north end of the gyro produces a downwardforce on the south end to causes a westerly precession of the north end. The result, for each arrangement, will be the same.

1.4.1 Bottom-heavy control

Figure 1.8(b) illustrates the principle of precession caused by gravity acting on the bottomweighted spin axis of a gyroscope. The pendulous weight will always seek the centre of gravity and in so doing will exert a torque about the gyro horizontal axis. Because of the earth's rotation and gyro rigidity, the pendulum will cause the gravity control to move away from the centre of gravity. The spinner is rotating clockwise, when viewed from the south end, and therefore, precession, caused by the gravitational force exerted on the spin axis, will cause the northeast end of the spin axis to move to the east when it is below the horizontal. A reciprocal action will occur causing the northeast end of the spin axis to precess towards the west when above the horizontal.

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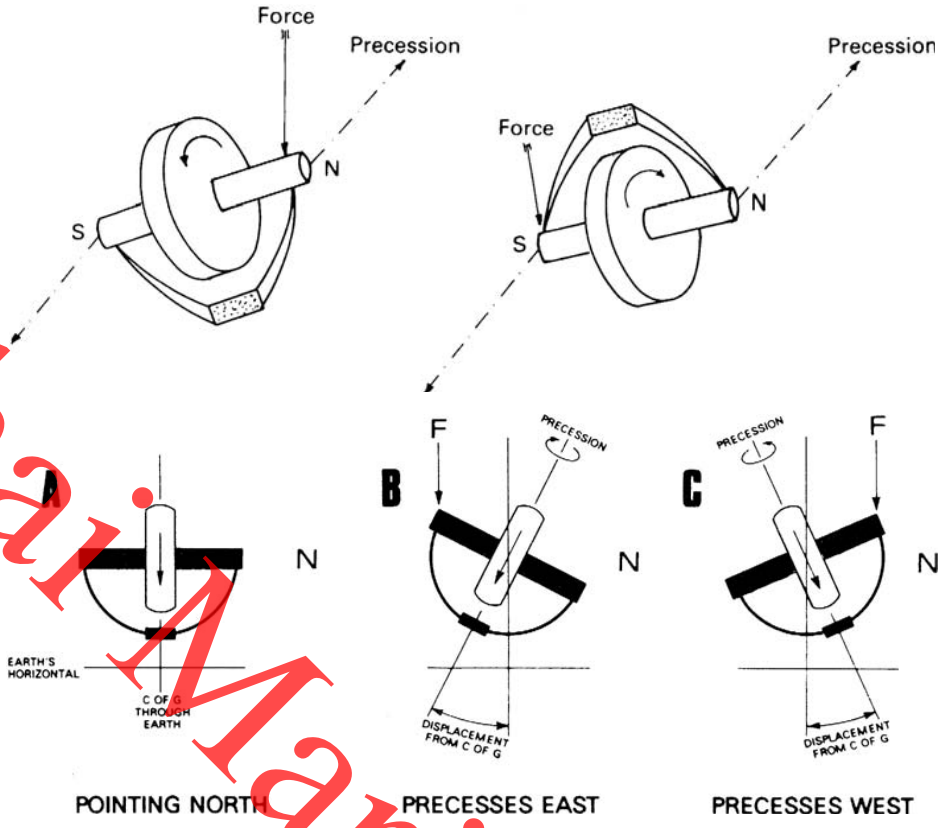

Figure 1.8 (a) Methods of gravity control: bottom-heavy principal and top-heavy control. (b) Principle of gravity control. (Reproduced courtesy of S. G. Brown Ltd.)

The spin axis will always appear to tilt with its north end away from the earth (up) when to the east of the meridian, and its north end towards the earth (down) when to the west of the meridian (see Figure 1.9).

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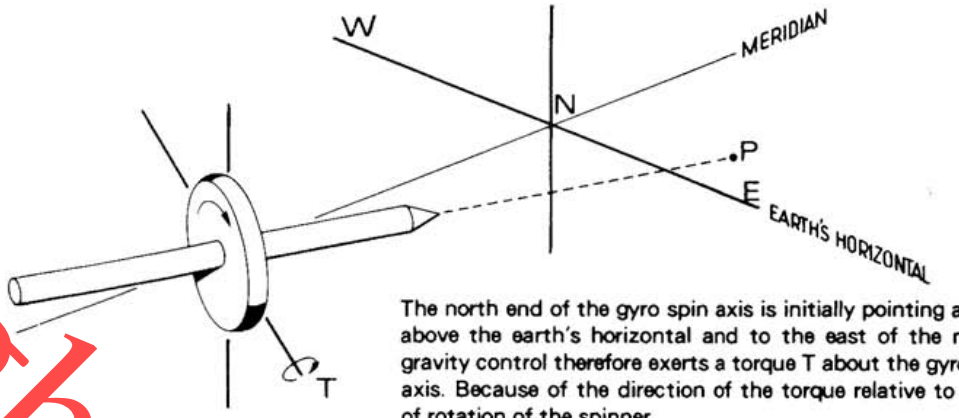
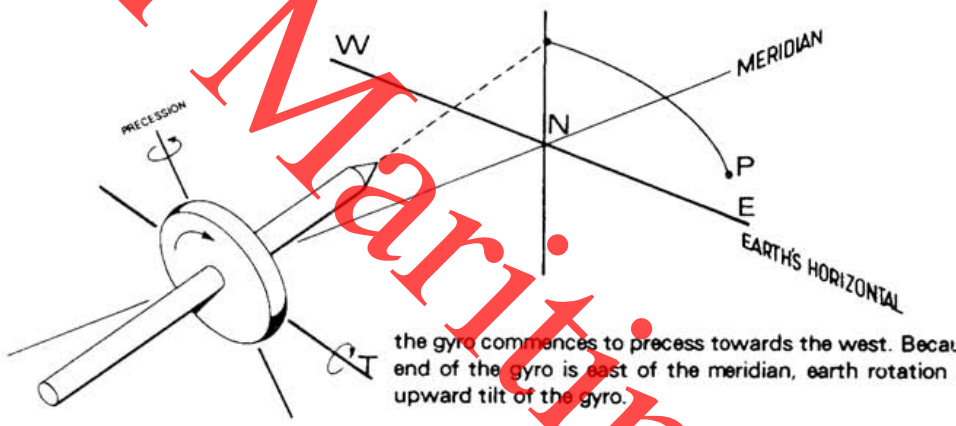
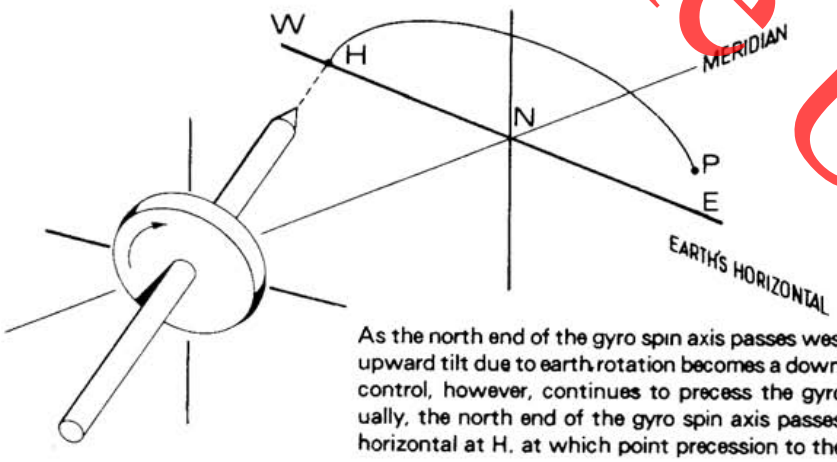


The north end of the gyro spin axis is initially pointing at P, which is above the earth's horizontal and to the east of the meridian. The gravity control therefore exerts a torque T about the gyro's horizontal axis. Because of the direction of the torque relative to the direction of rotation of the spinner,



the gyro commences to precess towards the west. Because the north end of the gyro is east of the meridian, earth rotation results in an upward tilt of the gyro.



As the north end of the gyro spin axis passes west of the meridian, the upward tilt due to earth rotation becomes a downward tilt. The gravity control, however, continues to precess the gyro westwards. Eventually, the north end of the gyro spin axis passes through the earth's horizontal at H, at which point precession to the west ceases.

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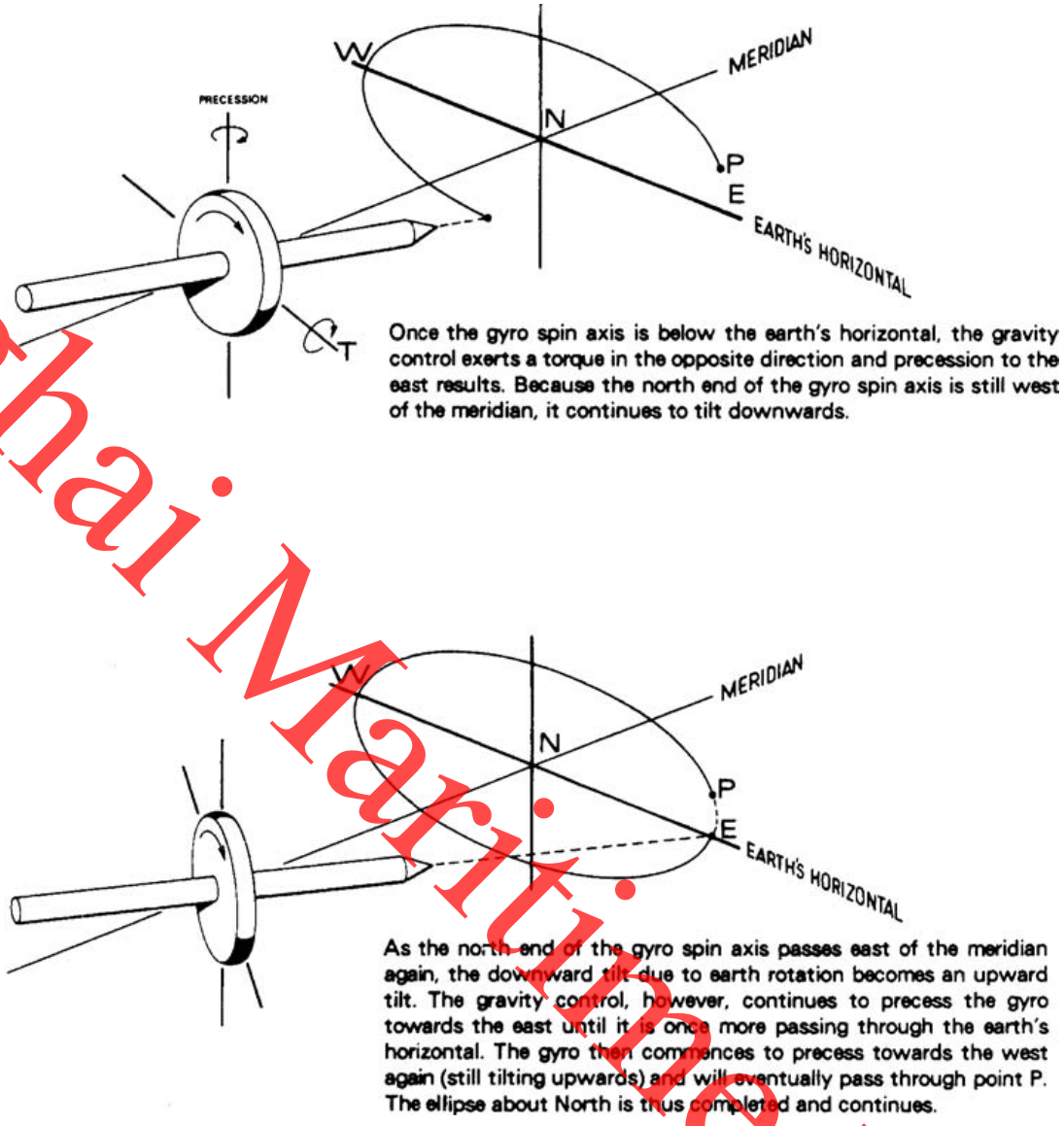
W
MERIDIAN
N
P
E
EARTH'S HORIZONTAL
PRECESSION
T
Once the gyro spin axis is below the earth's horizontal, the gravity control exerts a torque in the opposite direction and precession to the east results. Because the north end of the gyro spin axis is still west of the meridian, it continues to tilt downwards.
W
MERIDIAN
N
P
E
EARTH'S HORIZONTAL
As the north end of the gyro spin axis passes east of the meridian again, the downward tilt due to earth rotation becomes an upward tilt. The gravity control, however, continues to precess the gyro towards the east until it is once more passing through the earth's horizontal. The gyro then commences to precess towards the west again (still tilting upwards) and will eventually pass through point P. The ellipse about North is thus completed and continues.

Figure 1.9 Behaviour of the gravity-controlled gyro (undamped).

(Reproduced courtesy of S.G. Brown Ltd.)

This action causes the north end of the spin axis, of a gravity-controlled undamped gyro, to describe an ellipse about the meridian. Because it is undamped, the gyro will not settle on the meridian. Figure 1.9 shows this action for a gyro with a clockwise rotating spinner. The ellipse produced will be anticlockwise due to the constant external influences acting upon the gyro. The extent of the ellipse will, however, vary depending upon the initial displacement of the gyro spin axis from the meridian and from the earth's horizontal. The term 'north-seeking' is given to the undamped gravity controlled gyro mechanism because the northeast end of the spin axis describes an ellipse around the North Pole but never settles. Obviously such a gyro is not suitable for use as a precise north reference compass aid.

1.4.2 The north-settling gyro

The ellipse described by the previous gyro mechanism possesses a constant ratio of the major and minor axes. Clearly, therefore, if the extent of one axis can be reduced, the length of the other axis will be reduced in proportion. Under these conditions the gyro spin axis will eventually settle both on the meridian and horizontally. If the gyro axis is influenced by a second force exerting a damping torque about the vertical axis, so as to cause the spin axis to move towards the horizontal, it is obvious from

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Figure 1.10 that the minor axis of the ellipse will be reduced. As the north end of the spin axis moves to the west of the meridian, the earth's rotation will cause a downward tilt of the axis. This effect and the torque (Tv) will cause the gyro axis to meet the earth's horizontal at point H, which is a considerable reduction in the ellipse major axis. As Figure 1.10 clearly shows this action continues until the gyro settles in the meridian and to the surface of the earth, point N.

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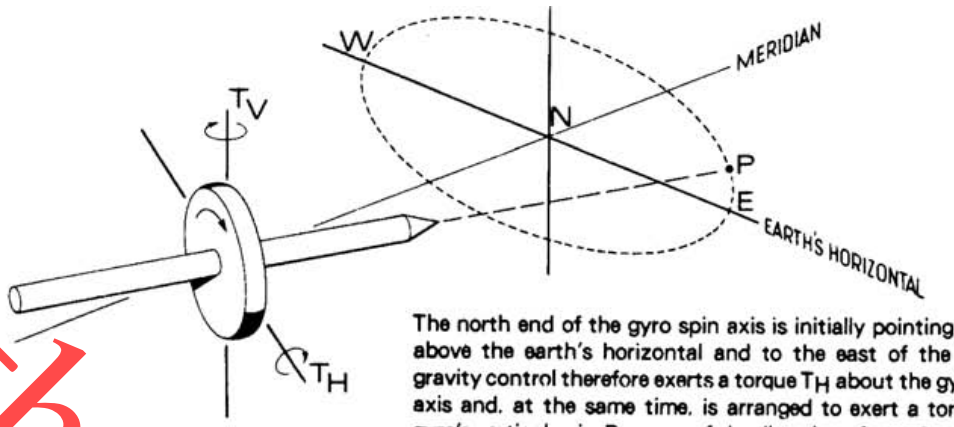
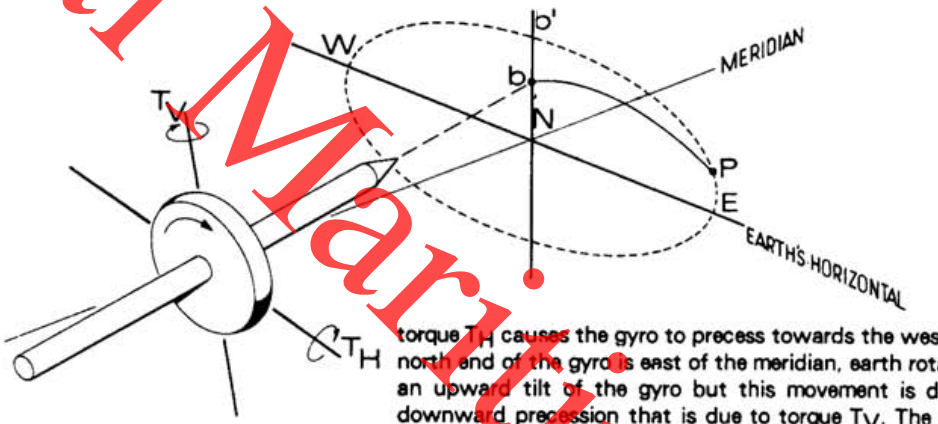
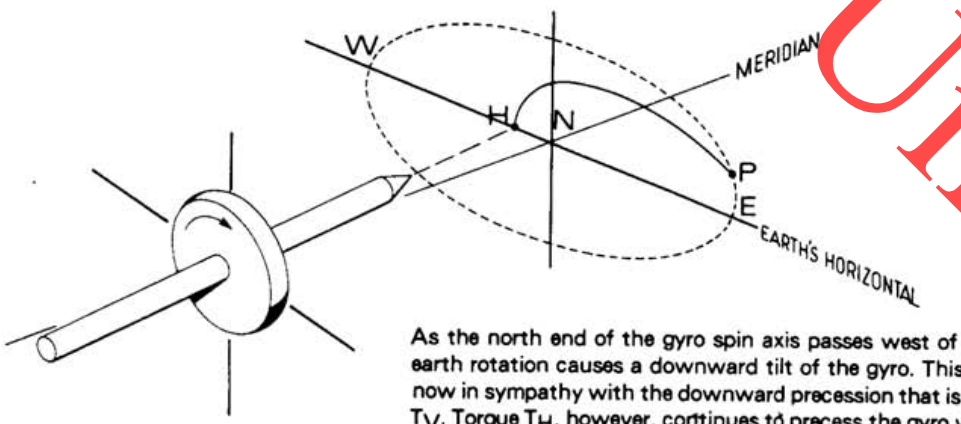


The north end of the gyro spin axis is initially pointing at P, which is above the earth's horizontal and to the east of the meridian. The gravity control therefore exerts a torque T_H about the gyro's horizontal axis and, at the same time, is arranged to exert a torque about the gyro's vertical axis. Because of the direction of rotation of the spinner,



torque T_H causes the gyro to precess towards the west. Because the north end of the gyro is east of the meridian, earth rotation results in an upward tilt of the gyro but this movement is damped by the downward precession that is due to torque T_V. The resultant path traced by the gyro spin axis is therefore Pb and not Pb', as would be the case without the damping torque T_V. Note that the downward (damping) precession becomes more evident as the north end of the gyro spin axis approaches the meridian. Note also that the minor axis of the ellipse is decreased by the amount bb'



As the north end of the gyro spin axis passes west of the meridian, earth rotation causes a downward tilt of the gyro. This movement is now in sympathy with the downward precession that is due to torque T_V. Torque T_H, however, continues to precess the gyro westwards so that the gyro spin axis passes through the earth's horizontal at H, at which point torques T_H and T_V cease. Note that the major axis of the ellipse is considerably decreased.

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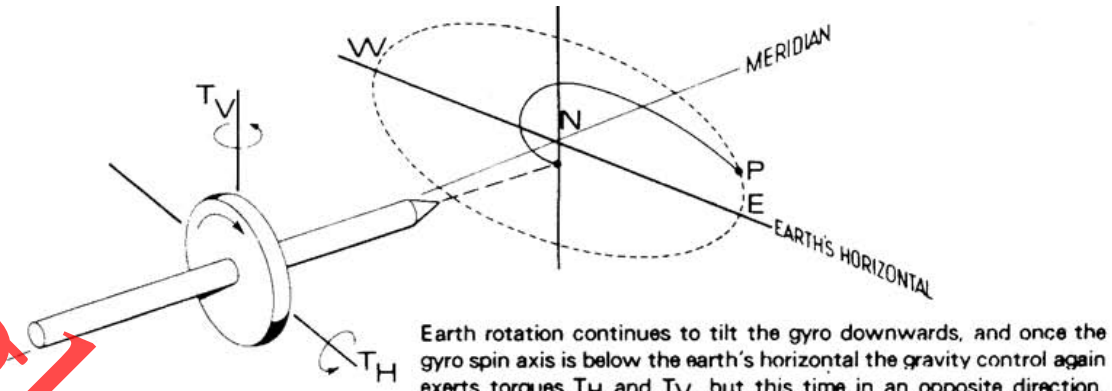
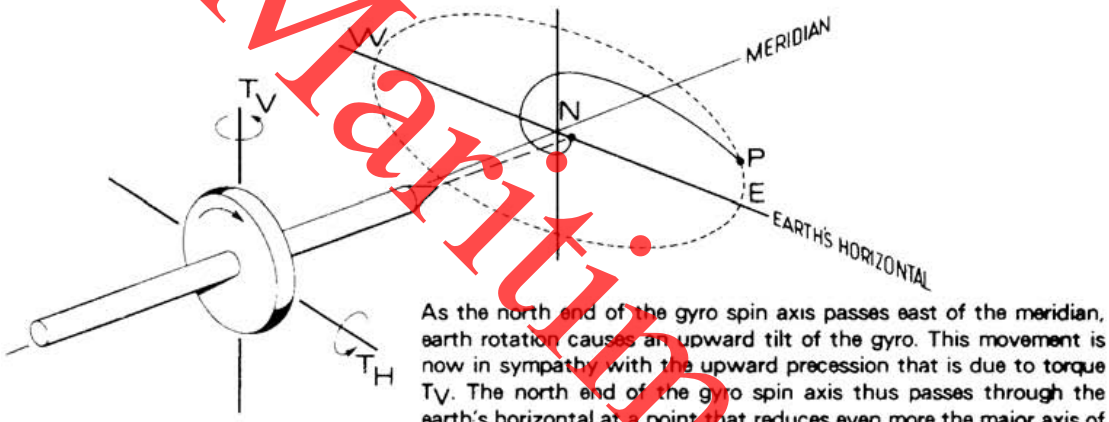
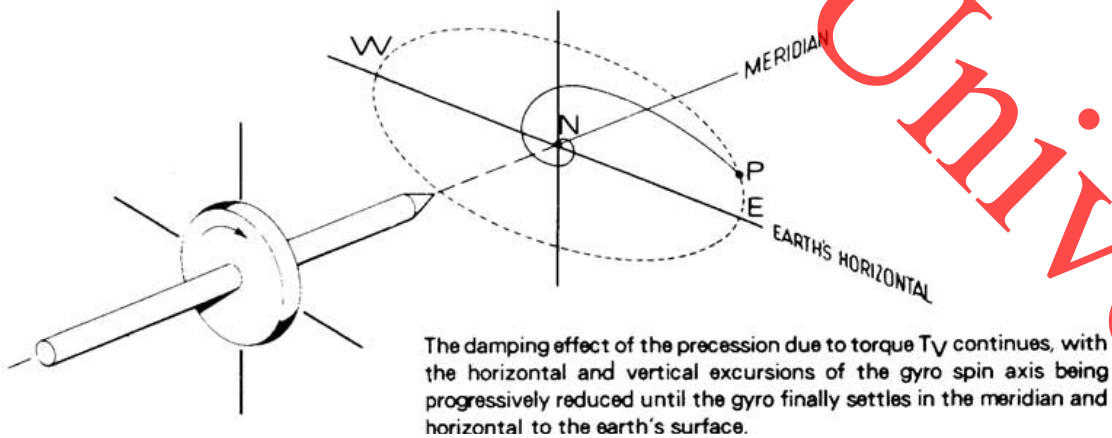


Earth rotation continues to tilt the gyro downwards, and once the gyro spin axis is below the earth's horizontal the gravity control again exerts torques T_H and T_V, but this time in an opposite direction. Torque T_H now causes precession eastwards, whilst torque T_V causes precession upwards and thus damps the downward tilt that is due to earth rotation. The resultant movement of the gyro causes the north end of the gyro spin axis to pass through the meridian at a point that reduces even more the minor axis of the ellipse.



As the north end of the gyro spin axis passes east of the meridian, earth rotation causes an upward tilt of the gyro. This movement is now in sympathy with the upward precession that is due to torque T_V. The north end of the gyro spin axis thus passes through the earth's horizontal at a point that reduces even more the major axis of the ellipse.



The damping effect of the precession due to torque T_V continues, with the horizontal and vertical excursions of the gyro spin axis being progressively reduced until the gyro finally settles in the meridian and horizontal to the earth's surface.

Figure 1.10 Behaviour of the gravity-controlled gyro (damped).

(Reproduced courtesy of S.G. Brown Ltd.)

1.4.3 Top-heavy control

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Whereas the previous compass relies on a bottom-weighted spin axis and a clockwise spinning rotor to produce a north-settling action, other manufacturers design their gyrocompasses to be effectively top-weighted and use an anticlockwise spinning rotor. But adding a weight to the top of the rotor casing produces a number of undesirable effects. These effects become pronounced when a ship is subjected to severe movement in heavy weather. To counteract unwanted effects, an 'apparent' top weighting of the compass is achieved by the use of a mercury fluid ballistic contained in two reservoirs or ballistic pots.

As shown in Figure 1.11, each ballistic pot, partly filled with mercury, is mounted at the north and south sides of the rotor on the spin axis. A small-bore tube connects the bases of each pot together providing a restricted path for the liquid to flow from one container to the other. The ballistic system is mounted in such a way that, when the gyro tilts, the fluid will also tilt and cause a displacement of mercury. This action produces a torque about the horizontal axis with a resulting precession in azimuth.

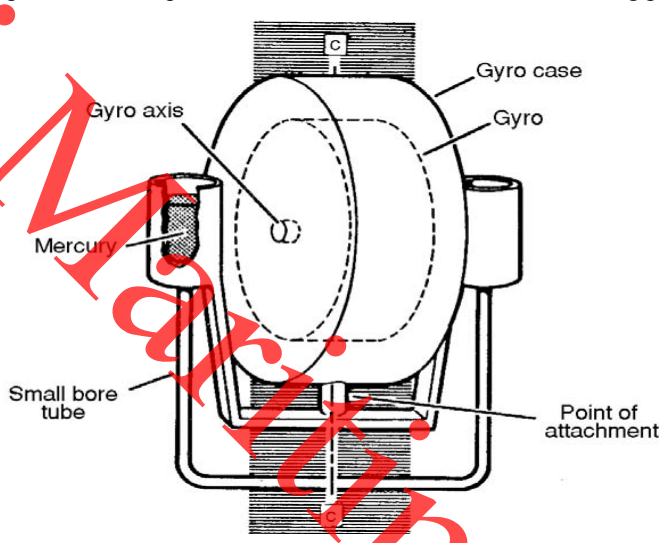

Figure 1.11 A method of applying 'offset damping' to the gyro wheel.
(Reproduced courtesy of Sperry Ltd.)

Consider a controlled gyroscope to be at the equator with its spin axis east west as shown in Figure 1.12. As the earth rotates from west to east the gyro will appear to tilt about its horizontal axis and the east end will rise forcing mercury to flow from pot A to pot B. The resulting imbalance of the ballistic will cause a torque about the horizontal axis. This in turn causes precession about the vertical axis and the spin axis will move in azimuth towards the meridian.

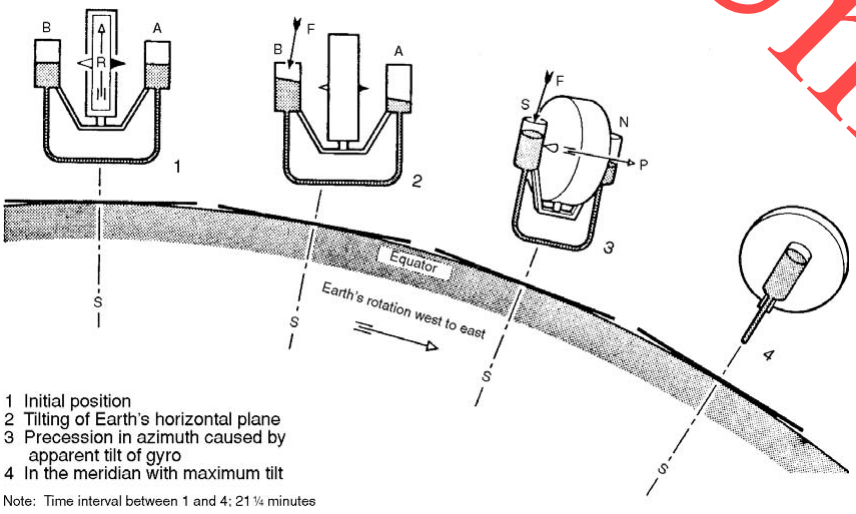

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Figure 1.12 Precession of a controlled gyroscope at the equator.

The right-hand side of the gyro spin axis now moves towards the north and is referred to as the north end of the spin axis. Without the application of additional forces, this type of gyro is northseeking only and will not settle in the meridian. The north end of the spin axis will therefore describe an ellipse as shown in Figure 1.9.

As the extent of the swings in azimuth and the degree of tilt are dependent upon each other, the gyro can be made to settle by the addition of an offset control force.

1.5 A practical gyrocompass

The apparent tilting of the gyroscope can be reduced by producing an offset controlling force, which in effect creates 'anti-tilt' precession allowing the unit to settle in the meridian. This is achieved by creating a force about the vertical axis to cause precession about the horizontal axis. This is achieved, in this gyro system, by offsetting the mercury ballistic controlling force slightly to the east of the vertical. The point of offset attachment must be precise so that damping action causes the gyro to settle exactly in the meridian. A comparatively small force is required to produce the necessary anti-tilt precession for the gyrocompass to be made suitable for use as a navigation instrument.

Figure 1.10 shows the curve now described by the north end of the damped gyrocompass which will settle in the meridian. An alternative and more commonly used method of applying anti-tilt damping is shown in Figure 1.13.

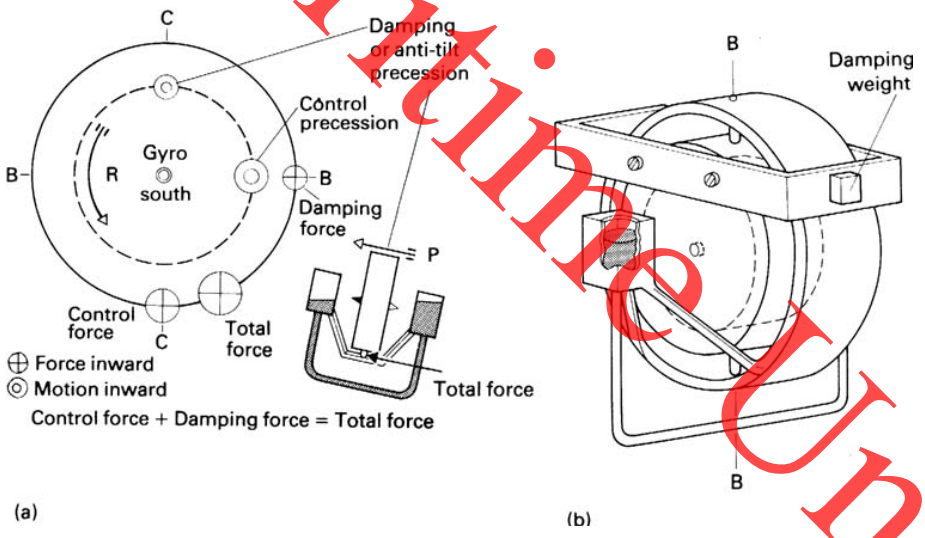

Figure 1.13 (a) Effect of control force plus damping force.(b) An alternative method of applying offset damping. (Reproduced courtesy of Sperry Ltd.)

Damping gyroscopic precession by the use of weights provides a readily adjustable system for applying damping. The period of gyro damping is directly related to the size of the damping force, and thus the weight. If the weight is increased, the damping percentage will be increased. The effect of alternative damping application is illustrated in Figure 1.14.

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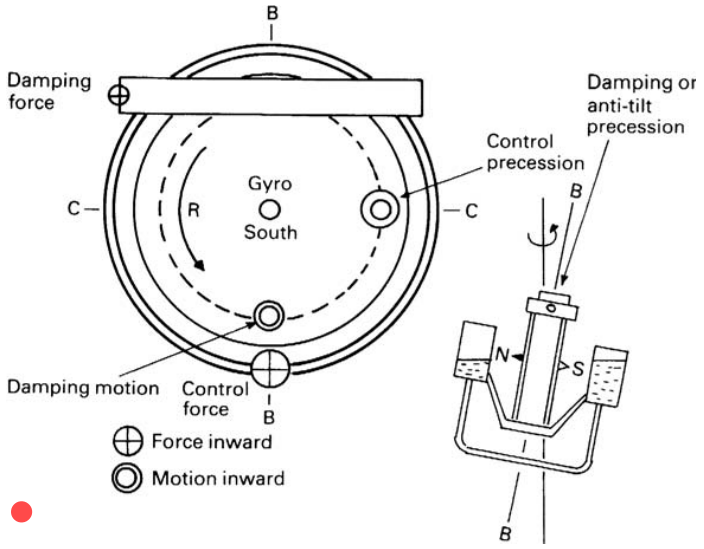

Figure 1.14 The effects of alternative damping application.

The amount of damping required depends upon the rate of tilt of the gyro axle and as such will be affected by latitude. As has been shown previously, tilt is a maximum at the equator. It follows, therefore, that damping should also be a maximum at the equator. However, the damping period will always remain constant, at approximately 86 min for some gyros, despite the change of amplitude of successive swings to east and west of the gyro axle. All gyrocompasses therefore require time to settle. Figure 1.15 shows a typical settling curve for a gyro possessing a damping period of greater than 80 min. The time taken for one oscillation, from A1 to A3 is termed the natural period of the compass.

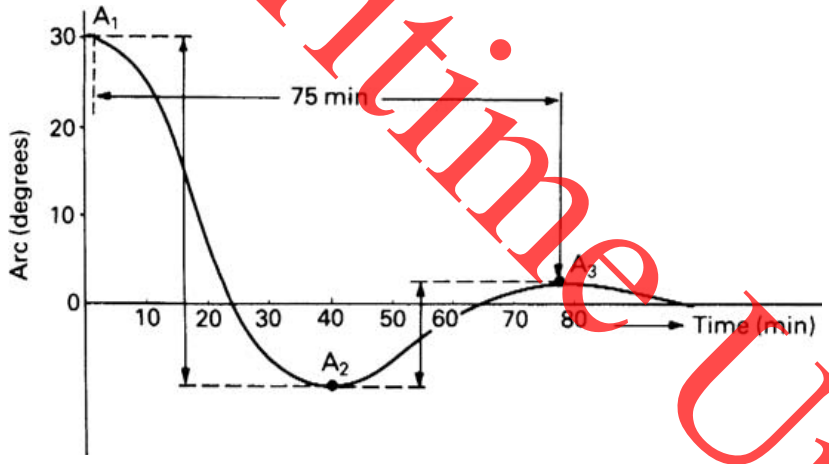

Figure 1.15 The settling curve of a typical gyro compass with a 75-min period.

1.5.1 The amount of tilt remaining on a settled gyro

The settling curve traced by the north end of the gyrospin axis illustrated in Figure 1.10 assumes that the gyrocompass is situated at the equator and will, therefore, not be affected by gyro tilt. It is more likely that a vessel will be at some north/south latitude and consequently drift must be taken into account.

It has been stated that for a gyrocompass in northern latitudes, the gyrospin axis will drift to the east of the meridian and tilt upwards. For any fixed latitude the easterly drift is constant. Westerly precession, however, is directly proportional to the angle of tilt of the rotor axle from the horizontal, which itself is dependent upon the deviation between it and the meridian. At some point the easterly deviation of the north end of the spin axis produces an angle of tilt causing a rate of westerly precession that is equal and opposite to the easterly drift. The north end, although pointing to the east of the meridian, is now

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stabilized in azimuth.

As the north end moves easterly away from the meridian both the rate of change of the tilt angle and the angle itself are increasing. The increasing angle of tilt produces an increasing rate of downward damping tilt until a point is reached where the upward and downward rates of tilt cancel.

The north end of the axle is above the horizontal although the rotor axle is stabilized. Figure 1.16 shows that the gyrocompass has settled, at point 0, to the east of the meridian and is tilted up.

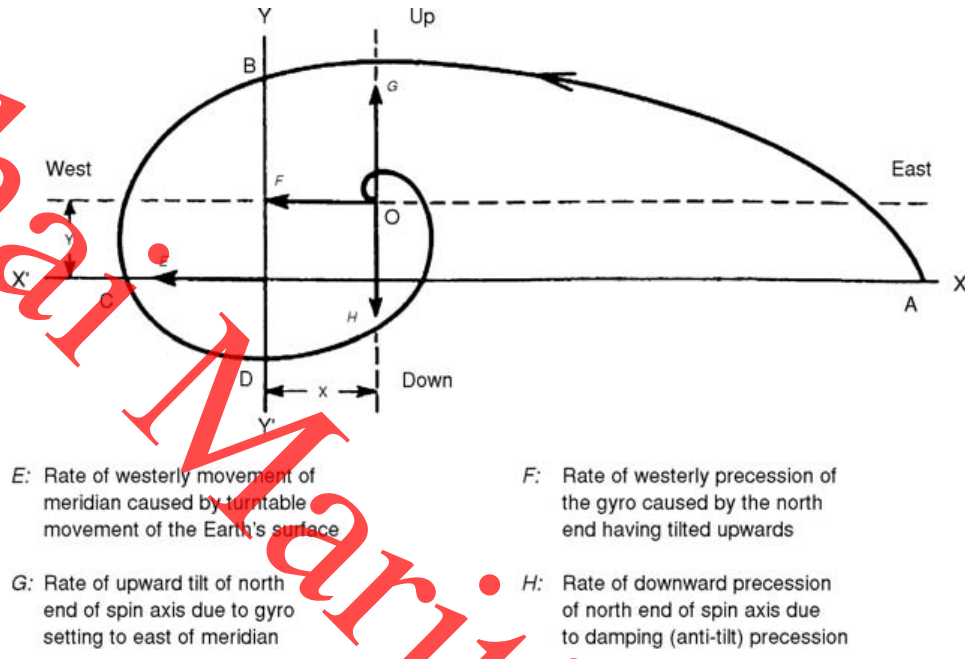

Figure 1.16 A curve showing error to the east and tilt caused by latitude on a settled gyrocompass. X is the angle away from the meridian and Y is the angle with the horizon (tilt).
(Reproduced courtesy of Sperry Ltd.)

The extent of the easterly and northerly (azimuth and tilt) error in the settled position is determined by latitude. An increase in latitude causes an increase in both the easterly deviation from the meridian and the angle of tilt above the horizontal. It is necessary therefore for latitude error, as the discrepancy is called, to be corrected in a gyrocompass.

As latitude increases, the effect of the earth's rotation becomes progressively less and consequently tilting of the rotor axle becomes less. It follows, therefore, that the rate of damping precession needed to cancel the rate of tilt, will also be less.

1.6 Follow-up systems

A stationary gravity-controlled gyrocompass will adequately settle close to the horizontal and near to the meridian, provided that it has freedom to move about the horizontal and vertical axes. However, if the gyrocompass is to be mounted on a ship, the base (phantom) ring needs to be capable of rotating through 360° without introducing torque about the vertical axis.

Freedom about the vertical axis is particularly difficult to achieve without introducing torque to the system. The most common way of permitting vertical-axis freedom is to mount the gyro in a vertical ring with ball bearings on the top and base plates. Obviously the weight of the unit must be borne on the lower bearing, which can create considerable friction and introduce torque. A number of methods have been developed to eliminate torque about the vertical axis. These include the use of high tensile

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torsion wires and buoyancy chambers, as described for each compass later in this chapter.

1.7 Compass errors

The accuracy of a gyrocompass is of paramount importance, particularly under manoeuvring situations where the compass is interfaced with collision-avoidance radar. An error, either existing or produced, between the actual compass reading and that presented to the radar could produce potentially catastrophic results. Assuming that the compass has been correctly installed and aligned, the static compass errors briefly listed below, should have been eliminated. They are, however, worthy of a brief mention.

1.7.1 Static errors

An alignment error can be:

- an error existing between the indicated heading and the vessel's lubber line
- an error existing between the indicated lubber line and the fore and aft line of the vessel.

Both of these errors can be accurately eliminated by critically aligning the compass with the ship's lubber line at installation.

Transmission error

An error existing between the indicated heading on the master compass and the heading produced by any remote repeater is a transmission error. Transmission errors are kept to a minimum by the use of multispeed pulse transmission.

Variable errors

Variable compass errors can effectively be classified into two groups.

- Dynamic errors that are caused by the angular motion of the vessel during heavy weather and
- manoeuvring.
- Speed/latitude errors that are caused by movement of the vessel across the earth's surface.

The magnitude of each error can be reduced to some extent as shown in the following text.

1.7.2 Dynamic errors

Rolling error

The gyrocompass is made to settle on the meridian under the influence of weights. Thus it will also be caused to shift due to other forces acting upon those weights. When a vessel rolls, the compass is swung like a pendulum causing a twisting motion that tends to move the plane of the sensitive element towards the plane of the swing. For a simple explanation of the error consider the surge of mercury caused in both the north and south reservoirs by a vessel rolling. If the ship is steaming due north or south, no redistribution of mercury occurs due to roll and there will be no error (see Figure 1.17).

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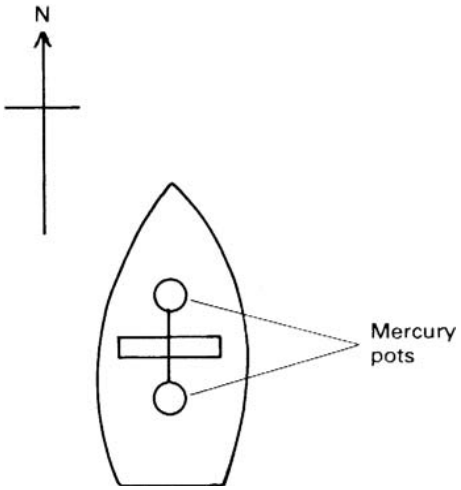

Figure 1.17 A ship steaming due north or south produces no roll error.

But with a ship steaming due east or west, maximum lateral acceleration occurs in the north/south direction causing precession of the compass. However, rolls to port and starboard are equal, producing equivalent easterly and westerly precession. The resulting mean-error is therefore zero, as illustrated in Figure 1.18.

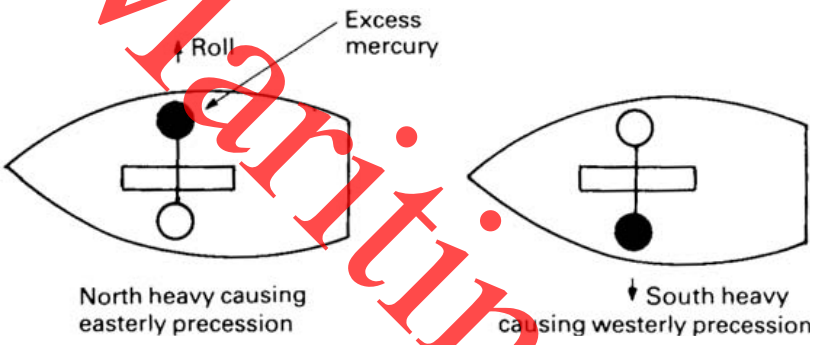

Figure 1.18 Precession rates created by a rolling vessel on an east/west course are equal and will cancel.

If the ship is on an intercardinal course the force exerted by the mercury (or pendulum) must be resolved into north/south and east/west components (see Figure 1.19).

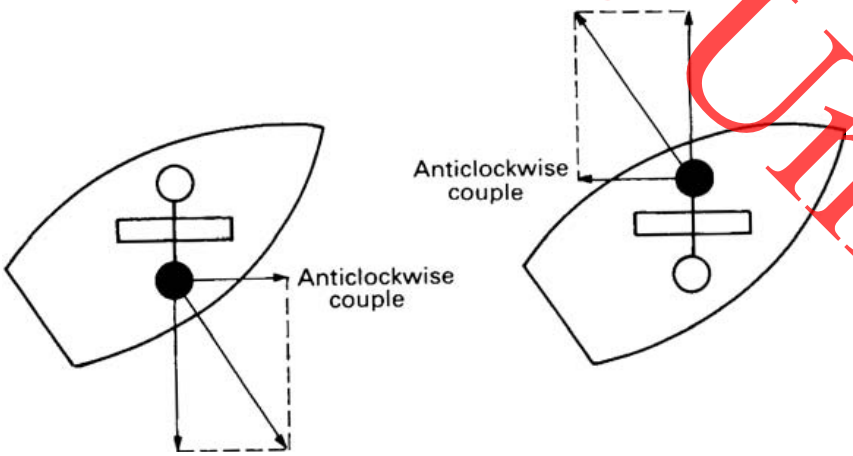

Figure 1.19 For a vessel on an intercardinal course, rolling produces an anticlockwise torque.

The result of the combined forces is that precession of the compass occurs under the influence of an effective anticlockwise torque. Damping the pendulum system can dramatically reduce rolling error. In a top-heavy gyrocompass, this is achieved by restricting the flow of mercury between the two pots. The

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damping delay introduced needs to be shorter than the damping period of the compass and much greater than the period of roll of the vessel. Both of these conditions are easily achieved.

Electrically-controlled compasses are roll-damped by the use of a viscous fluid damping the gravity pendulum. Such a fluid is identified by a manufacturer's code and a viscosity number. For example, in the code number 200/20, 200 refers to the manufacturer and 20 the viscosity. A higher second number indicates a more viscous silicon fluid. One viscous fluid should never be substituted for another bearing a different code number. Additionally since roll error is caused by lateral acceleration, mounting the gyrocompass low in the vessel and as close as possible to the centre of roll will reduce this error still further.

Manoeuvring (ballistic) error

This error occurs whenever the ship is subject to rapid changes of speed or heading. Because of its pendulous nature, the compass gravity control moves away from the centre of gravity whenever the vessel changes speed or alters course. Torque's produced about the horizontal and vertical axis by manoeuvring cause the gyro mechanism to precess in both azimuth and tilt. If the ship is steaming due north and rapidly reducing speed, mercury will continue to flow into the north pot, or the gravity pendulum continues to swing, making the gyro spin axis north heavy and thus causing a precession in azimuth.

In Figure 1.20 the decelerating vessel causes easterly precession of the compass. Alternatively if the ship increases speed the compass precesses to the west.

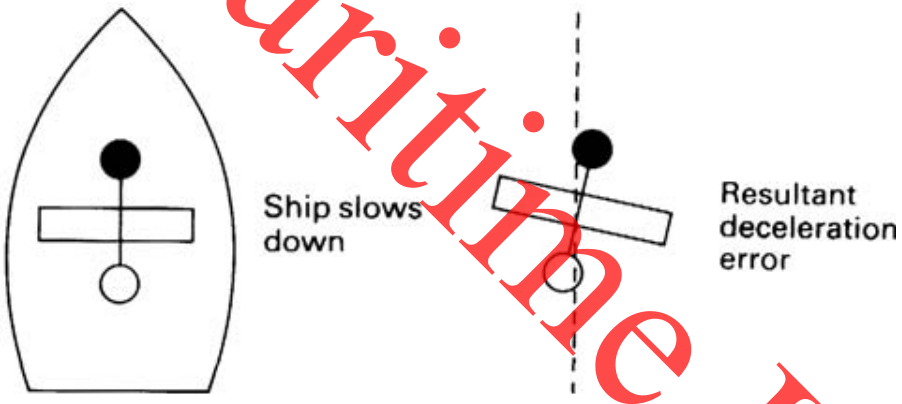

Figure 1.20 Resultant easterly error caused by the vessel slowing down.

Latitude (damping) error

Latitude error is a constant error, the magnitude of which is directly proportional to the earth's rotation at any given latitude. It is, therefore, present even when the ship is stationary. As has previously been stated, a gyrocompass will always settle close to the meridian with an error in tilt. To maintain the gyro pointing north it must be precessed at an angular rate varying with latitude. At the equator the earth's linear speed of rotation is about 900 knots and rotation from west to east causes a fixed point to effectively move at 900·cos(latitude) knots in an easterly direction. For any latitude (λ) the rate of earth spin is $\omega = 15° \, h^{-1}$. This may be resolved into two components, one about the true vertical at a given latitude ($\omega \sin\lambda$) and the other about the north/south earth surface horizontal at a given latitude ($\omega \cos\lambda$) as illustrated in Figure 1.21.

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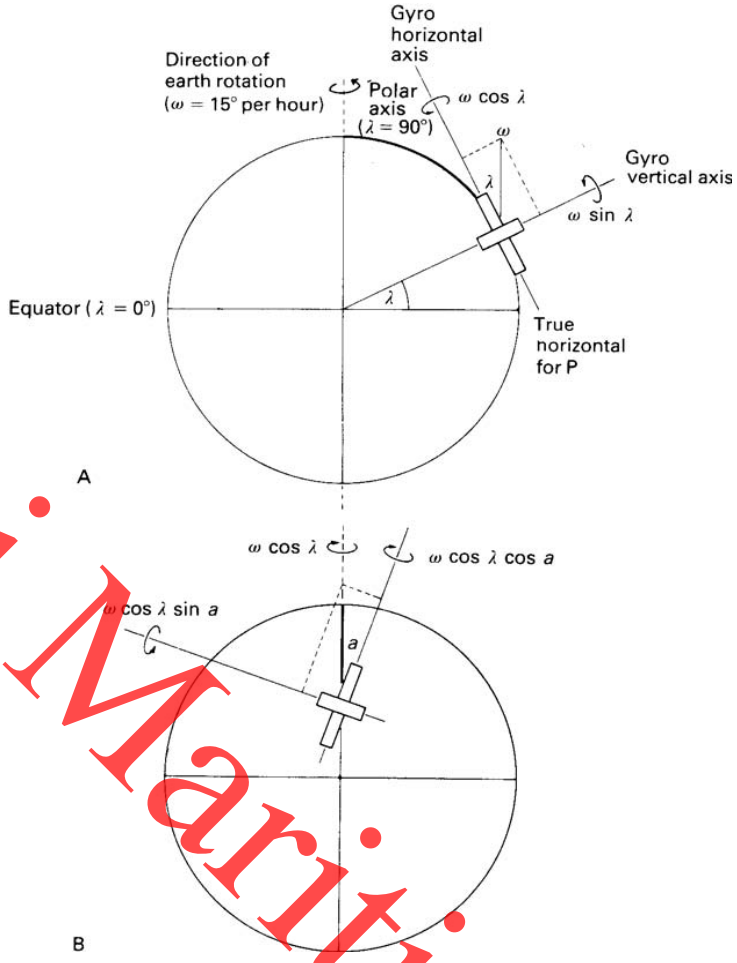

Figure 1.21 Apparent movement of a gyro. (Reproduced courtesy S. G. Brown Ltd.)

The component of the earth's rotation about the north/south horizontal may be resolved further into two components mutually at right angles to each other. The first component is displaced $a°$ to the east of the meridian producing a rate of spin $\omega\cos\lambda\sin a°$, whilst the other is $90 - a°$ to the west of north to produce a rate of spin $\omega\cos\lambda\cos a°$.

Correction for latitude error requires that a torque be applied to precess the gyro at an angular rate, varying with latitude, to cancel the error. This will be an external correction that can be either mechanical or electronic. For mechanical correction, a weight on the gyro case provides the necessary torque. The weight, or 'mechanical latitude rider', is adjustable thus enabling corrections to be made for varying latitudes. Another method of mechanical correction is to move the lubber line by an amount equal to the error. Latitude correction in a bottom-weighted compass is achieved by the introduction of a signal proportional to the sine of the vessel's latitude, causing the gyro ball to precess in azimuth at a rate equal and opposite to the apparent drift caused by earth rotation.

Speed and course error

If a vessel makes good a northerly or southerly course, the north end of the gyro spin axis will apparently tilt up or down since the curvature of the earth causes the ship to effectively tilt bows up or down with respect to space. Consider a ship steaming due north. The north end of the spin axis tilts upwards causing a westerly precession of the compass, which will finally settle on the meridian with some error in the angle, the magnitude of which is determined by the speed of the ship. On a cardinal course due east or west, the ship will display a tilt in the east/west plane of the gyro and no tilting of the gyro axle occurs – hence no speed error is produced. The error varies, therefore, with the cosine of the

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ship's course. Speed/course gyrocompass error magnitude must also be affected by latitude and will produce an angle of tilt in the settled gyro. Hence latitude/course /speed error is sometimes referred to as LCS error.

1.7.3 Use of vectors in calculating errors

With reference to Figure 1.22,

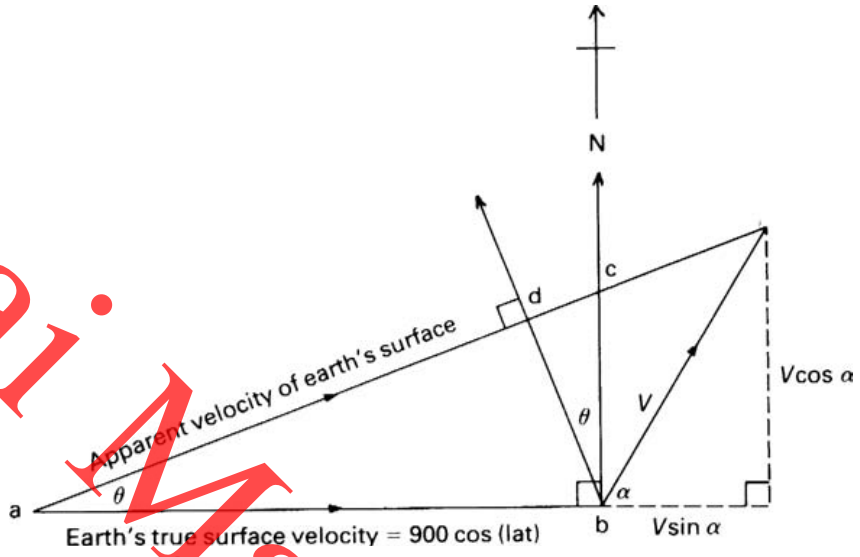

Figure 1.22 Use of vectors in calculating errors

V = ships speed in knots

$V \sin\alpha$ = easterly component of speed

α = ships course

$V \cos\alpha$ = northerly component of speed

angle acb = angle dcb

angle abc = angle bdc = 90°

angle bac = angle cbd = θ = error

In triangle abc:

$$\text{Error in degrees} = \text{angle bac} = \theta = \tan^{-1} \frac{V \cos (\text{course})}{900 \cos (\text{latitude}) + V \sin (\text{course})}$$

Obviously the ship's speed is very much less than the earth's surface velocity therefore:

$$\tan \theta \simeq \frac{V \cos (\text{course})}{900 \cos (\text{latitude})}$$

The angle θ may be approximately expressed in degrees by multiplying both side of the equation by a factor of 60. Now:

$$\text{approximate error in degrees} = \frac{V \cos (\text{course})}{15 \cos (\text{latitude})}$$

1.8 Top-heavy control master compass

Produced before the move towards fully sealed gyro elements, the Sperry SR120 gyrocompass (Figure 1.23) is a good example of an early top-heavy controlled system. The master compass consists of two

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main assemblies, the stationary element and the movable element.

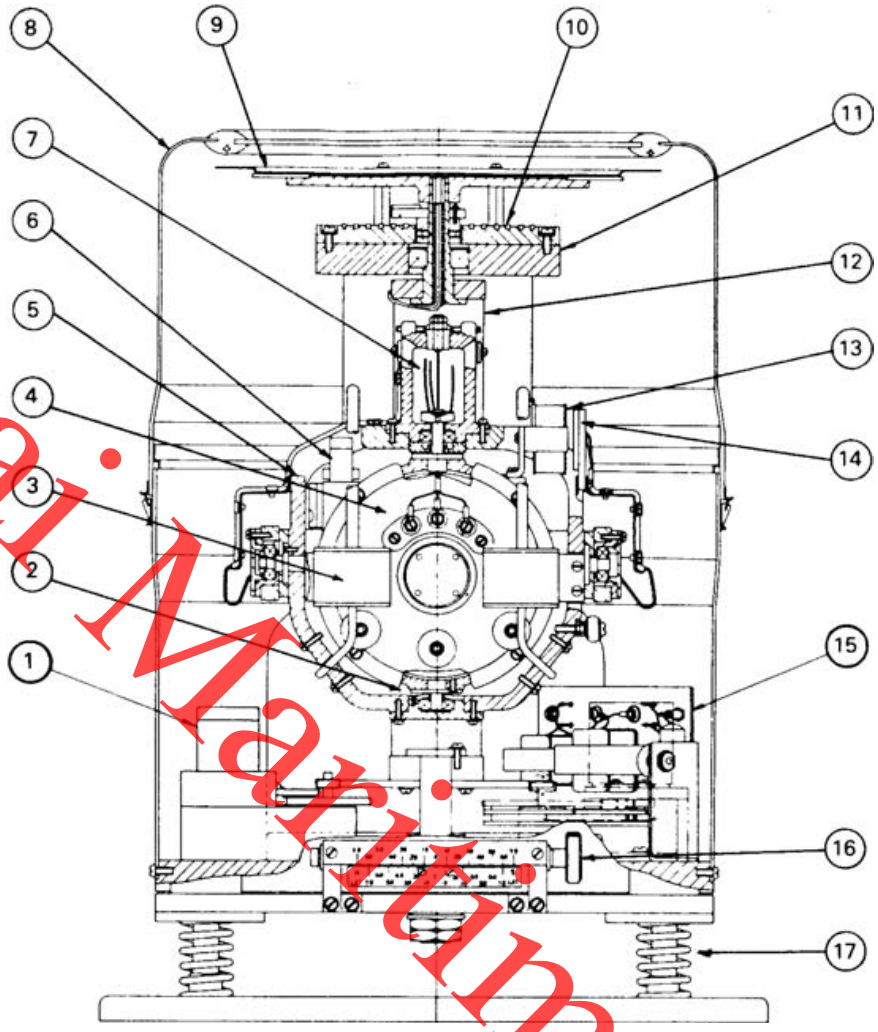

Figure 1.23 A south elevation sectional view of a Sperry master compass . Key:1. Stepper transmitter; 2. Support ball bearings; 3. Ballistic pots; 4.Rotor (encased); 5.Rotor case; 6. Damping weight; 7. Suspension wire; 8. Cover; 9.Compass card; 10.Slip rings; 11. Main support frame; 12. Phantom ring support assembly (cutaway); 13. Follow-up primary transformer; 14. Follow-up secondary transformer; 15. Follow-up amplifier; 16. Latitude corrector; 17. Spring/shock absorber assembly.

1.8.1 The stationary element

This is the main supporting frame that holds and encases the movable element. It consists of the main frame and base, together with the binnacle and mounting shock absorbers. The top of the main support frame (11) (Figure 1.23) holds the slip rings, lubber line and the scale illumination circuitry, whilst the main shaft, connected to the phantom ring (12), protrudes through the supporting frame to hold a compass card that is visible from above.

A high quality ball bearing race supports the movable element on the base of the main support frame in order that movement in azimuth can be achieved. The base of the whole assembly consists of upper and lower base plates that are connected at their centre by a shaft. Rotation of the upper plate in relation to the lower plate enables mechanical latitude correction to be made. The latitude corrector (16) is provided with upper and lower latitude scales graduated in 10 units, up to 70° north or south latitude, either side of zero. Latitude correction is achieved by mechanically rotating the movable element relative to the stationary element thus producing a shift in azimuth. The fixed scale of the latitude

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adjuster (16) is secured to the stationary element with a second scale fixed to the movable element. To set the correction value, which should be within 5° of the ship's latitude, is simply a matter of aligning the ship's latitude on the lower scale with the same indication on the upper scale of the vernier scale. Also supported by the base plate are the azimuth servomotor and gear train, and the bearing stepper transmitter.

1.8.2 The movable element

With the exception of the phantom ring, the movable element is called the sensitive element (Figure 1.24). At the heart of the unit is the gyro rotor freely spinning at approximately 12 000 rpm. The rotor is 110 mm in diameter and 60 mm thick and forms, along with the stator windings, a three-phase induction motor. Gyroscopic inertia is produced by the angular momentum of the rapidly spinning heavy rotor. Rotation is counter clockwise (counter earthwise) when viewed from the south end.

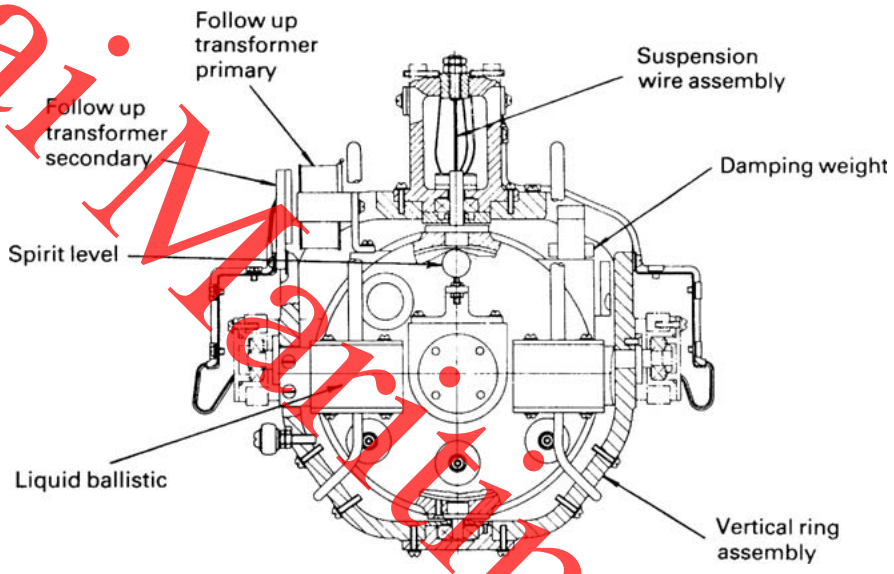

Figure 1.24 The compass sensitive element.

A sensitive spirit level graduated to represent 2 min of arc, is mounted on the north side of the rotor case. This unit indicates the tilt of the sensitive element. A damping weight is attached to the west side of the rotor case in order that oscillation of the gyro axis can be damped and thus enable the compass to point north.

The rotor case is suspended, along the vertical axis, inside the vertical ring frame by means of the suspension wire (7). This is a bunch of six thin stainless steel wires that are made to be absolutely free from torsion. Their function is to support the weight of the gyro and thus remove the load from the support bearings (2).

1.8.3 Tilt stabilization (liquid ballistic)

To enable the compass to develop a north-seeking action, two ballistic pots (3) are mounted to the north and south sides of the vertical ring. Each pot possesses two reservoirs containing the high density liquid 'Daifloil'. Each north/south pair of pots is connected by top and bottom pipes providing a total liquid/air sealed system that operates to create the effect of top heaviness.

Because the vertical ring and the rotor case are coupled to each other, the ring follows the tilt of the gyro spin axis. Liquid in the ballistic system, when tilted, will generate a torque which is proportional to the angle of the tilt. The torque thus produced causes a precession in azimuth and starts the northseeking action of the compass.

1.8.4 Azimuth stabilization (phantom ring assembly)

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Gyro freedom of the north/south axis is enabled by the phantom ring and gearing. This ring is a vertical circle which supports the north/south sides of the horizontal ring (on the spin axis) by means of high precision ball bearings.

A small oil damper (6) is mounted on the south side of the sensitive element to provide gyro stabilization during the ship's pitching and rolling.

The compass card is mounted on the top of the upper phantom ring stem shaft and the lower stem shaft is connected to the support ball bearings enabling rotation of the north/south axis. The azimuth gearing, located at the lower end of the phantom ring, provides freedom about this axis under a torque from the azimuth servomotor and feedback system.

1.8.5 Azimuth follow-up system

The system shown in Figure 1.25 enables the phantom ring to follow any movement of the vertical ring. The unit senses the displacement signal produced by misalignment of the two rings, and amplifies the small signal to a power level of sufficient amplitude to drive the azimuth servo rotor. Movement of the azimuth servo rotor causes rotation, by direct coupling, of the phantom ring assembly in the required direction to keep the two rings aligned.

The sensing element of the follow-up system is a transformer with an 'E'-shaped laminated core and a single primary winding supplied with a.c., and two secondary windings connected as shown in Figure 1.25. With the 'E'-shaped primary core in its central position, the phase of the e.m.f.s induced in the two secondaries is such that they will cancel, and the total voltage produced across R1 is the supply voltage only. This is the stable condition during which no rotation of the azimuth servo rotor occurs. If there is misalignment in any direction between the phantom and the vertical rings, the two e.m.f.s induced in the two secondaries will be unbalanced, and the voltage across R1 will increase or decrease accordingly.

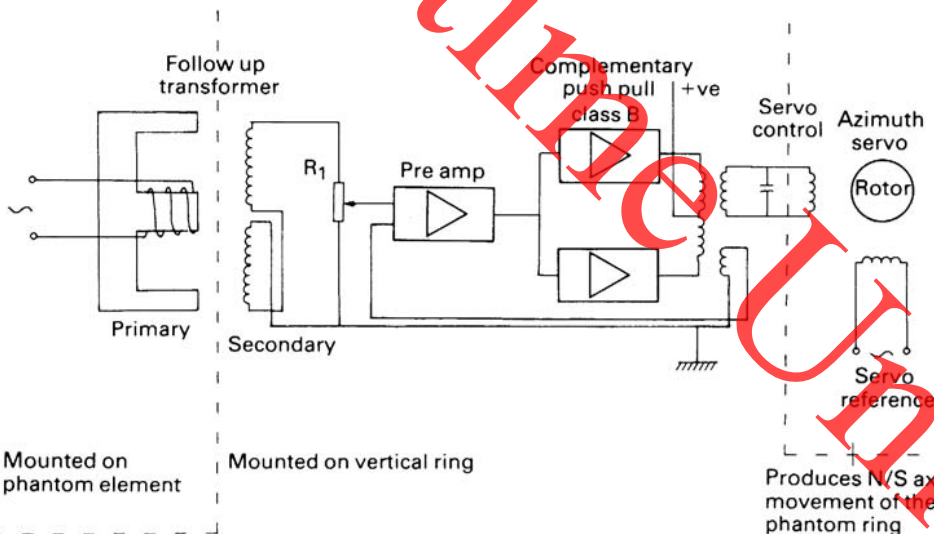

Figure 1.25 The Sperry compass azimuth follow-up circuit.

This error signal is pre-amplified and used to drive a complementary push/pull power amplifier producing the necessary signal level to cause the azimuth servo to rotate in the required direction to re-align the rings and thus cancel the error signal. Negative feedback from T2 secondary to the preamplifier ensures stable operation of the system.

Another method of azimuth follow-up control was introduced in the Sperry SR220 gyrocompass (Figure 1.26).

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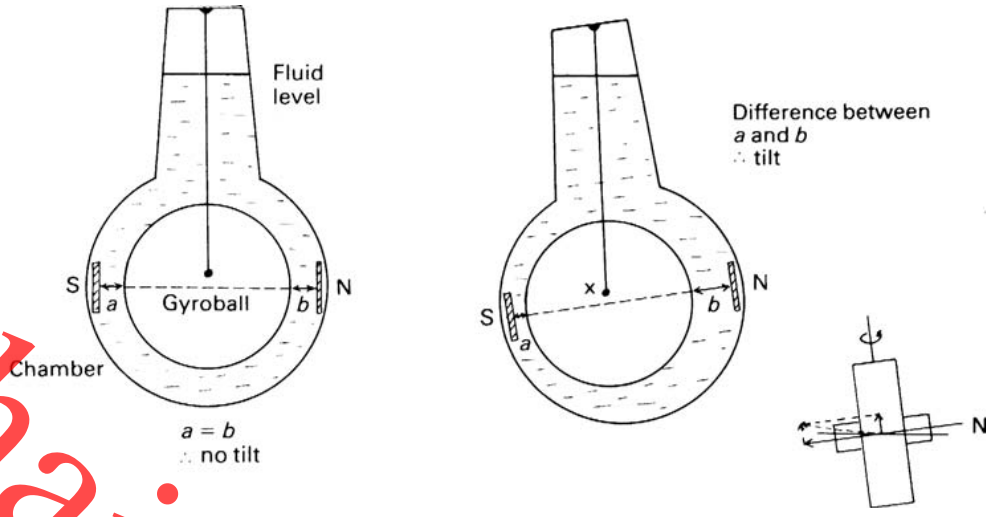

Figure 1.26 Simplified diagrams of the gyroball action in the Sperry SR220 gyrocompass.

In practice only a few millimetres separate the sphere from the sensitive element chamber. The point of connection of the suspension wire with the gyrosphere, is deliberately made to be slightly above the centre line of the sphere on the east–west axis. At the north and south ends of the horizontal axis are mounted the primary coils of the follow-up pick-off transformers. With no tilt present, the sphere centre line will be horizontal and central causing distance *a* to be equal to distance *b* producing equal amplitude outputs from the follow-up transformers which will cancel. Assuming the gyrocompass is tilted up and to the east of the meridian, the gyrosphere will take up the position shown in Figure 1.26. The sphere has moved closer to the south side of the chamber producing a difference in the distances *a* and *b*. The two pick-off secondary coils will now produce outputs that are no longer in balance. Difference signals thus produced are directly proportional to both azimuth and tilt error. Each pick-off transformer is formed by a primary coil mounted on the gyrosphere and secondary pick-off coils mounted on the sensitive element assembly. The primary coils provide a magnetic field, from the 110V a.c. supply used for the gyrowheel rotor, which couples with the secondary to produce e.m.f.s depending upon the relationship between the two coils.

Figure 1.27 shows that the secondary coils are wound in such a way that one or more of the three output signals is produced by relative movement of the gyrosphere. *X*=a signal corresponding to the distance of the sphere from each secondary coil; Φ =a signal corresponding to vertical movement; and θ = a signal corresponding to horizontal movement.

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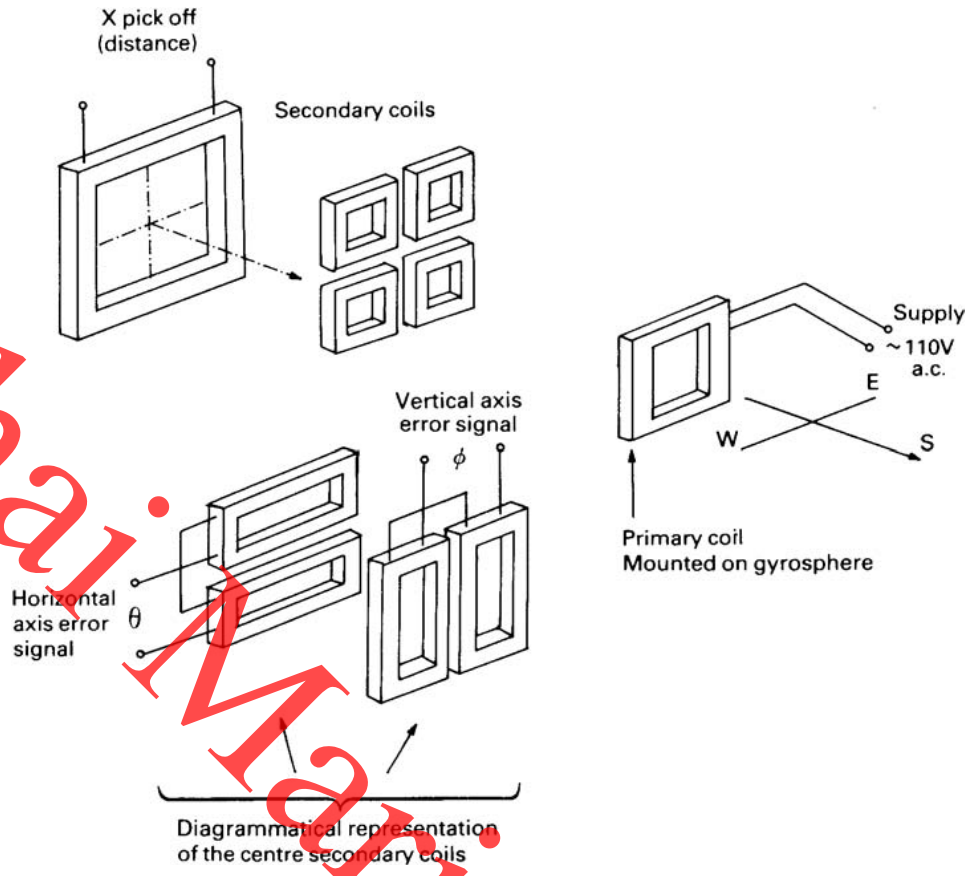

Figure 1.27 Follow-up signal pick-off coils.

In the complete follow-up system shown in Figure 1.28, the horizontal servomechanism, mounted on the west side of the horizontal ring, permits the sensitive element to follow-up the gyrosphere about the horizontal axis. This servo operates from the difference signal produced by the secondary pick-off coils, which is processed to provide the amplitude required to drive the sensitive element assembly in azimuth by rotating the phantom yoke assembly in the direction needed to cancel the error signal. In this way the azimuth follow-up circuit keeps the gyrosphere and sensitive element chamber in alignment as the gyro precesses.

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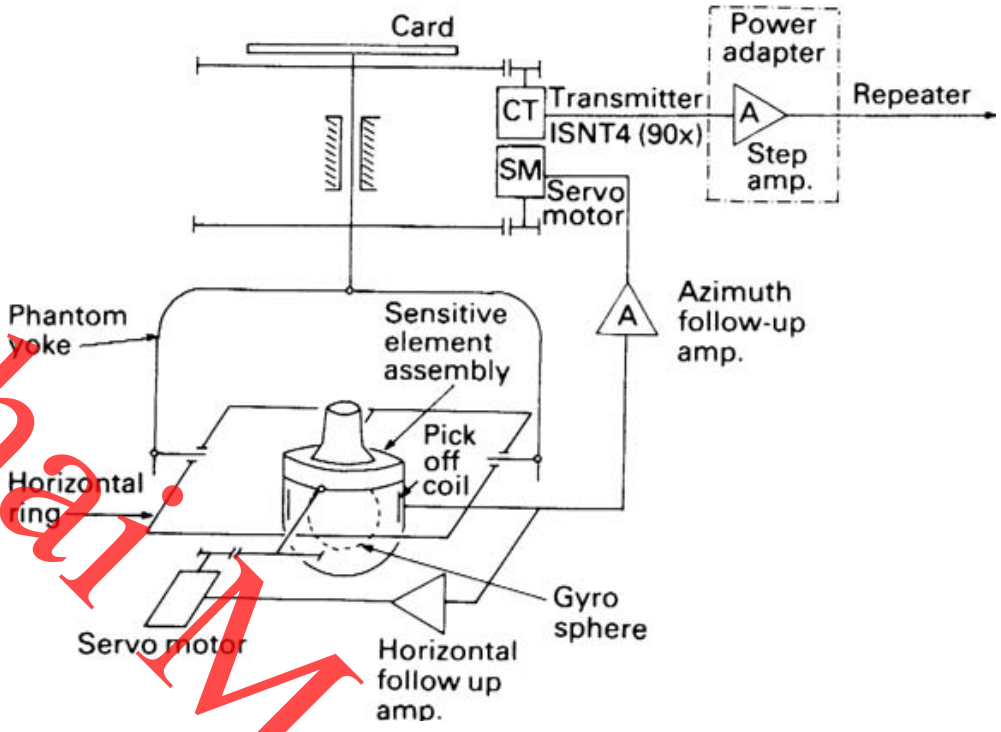

Figure 1.28 The Sperry SR220 follow-up system.

1.9 A digital controlled top-heavy gyrocompass system

In common with all other maritime equipment, the traditional gyrocompass is now controlled by a microcomputer. Whilst such a system still relies for its operation on the traditional principles already described, most of the control functions are computer controlled. The Sperry MK 37 VT Digital Gyrocompass (Figure 1.29) is representative of many gyrocompasses available. The system has three main units, the sealed master gyrocompass assembly, the electronics unit and the control panel.

The master compass, a shock-mounted, fluid-filled binnacle unit, provides uncorrected data to the electronics units which processes the information and outputs it as corrected heading and rate of turn data. Inside the three-gimbals mounting arrangement is a gyrosphere that is immersed in silicone fluid and designed and adjusted to have neutral buoyancy. This arrangement has distinct advantages over previous gyrocompasses.

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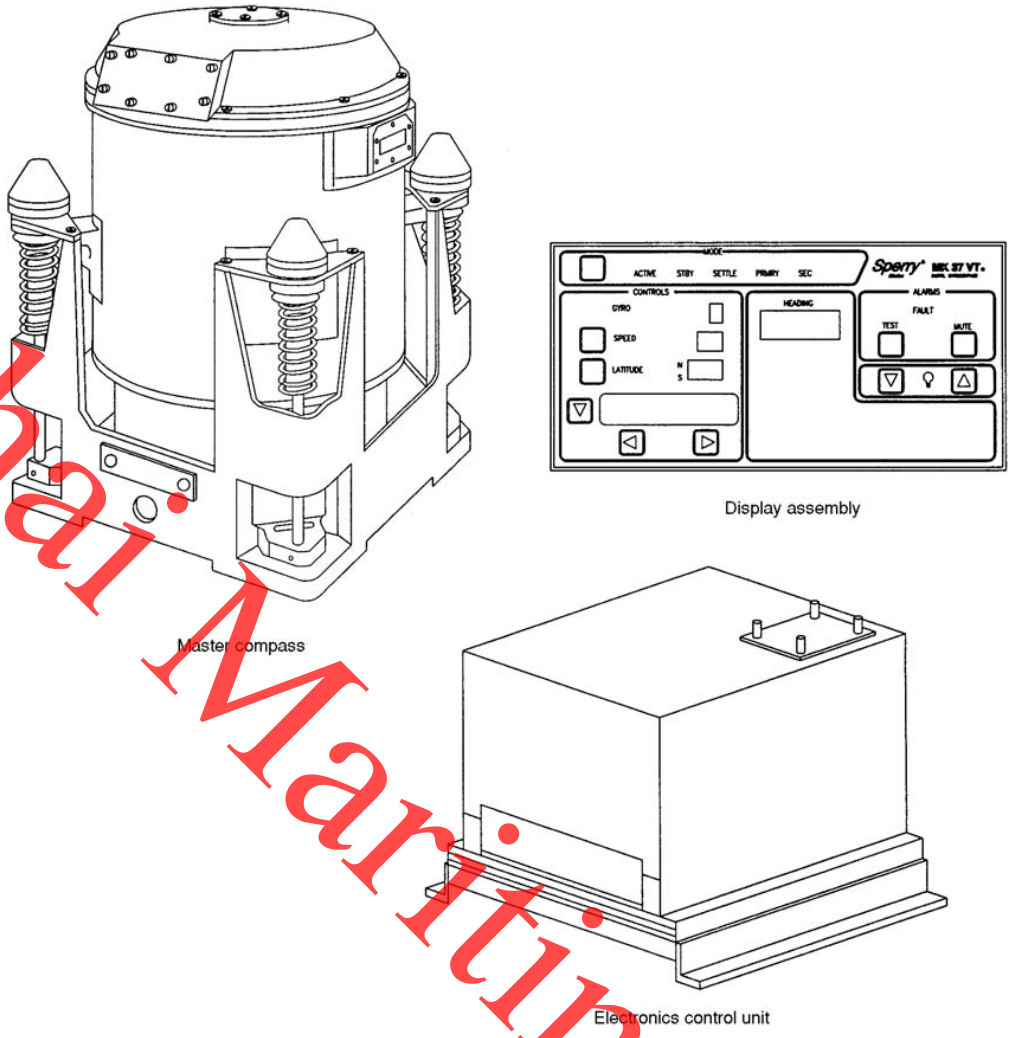

Figure 1.29 Sperry Mk 37 VT digital gyrocompass equipment.
(Reproduced courtesy of Litton Marine Systems.)

- The weight of the gyrosphere is removed from the sensitive axis bearings.
- The gyrosphere and bearings are protected from excessive shock loads.
- Sensitivity to shifts of the gyrosphere's centre of mass, relative to the sensitive axis, is eliminated.
- The effects of accelerations are minimized because the gyrosphere's centre of mass and the centre of buoyancy are coincident.

The system's applications software compensates for the effects of the ship's varying speed and local latitude in addition to providing accurate follow-up data maintaining yoke alignment with the gyrosphere during turn manoeuvres.

1.9.1 Control panel

All command information is input via the control panel, which also displays various data and system indications and alarms (see Figure 1.30).

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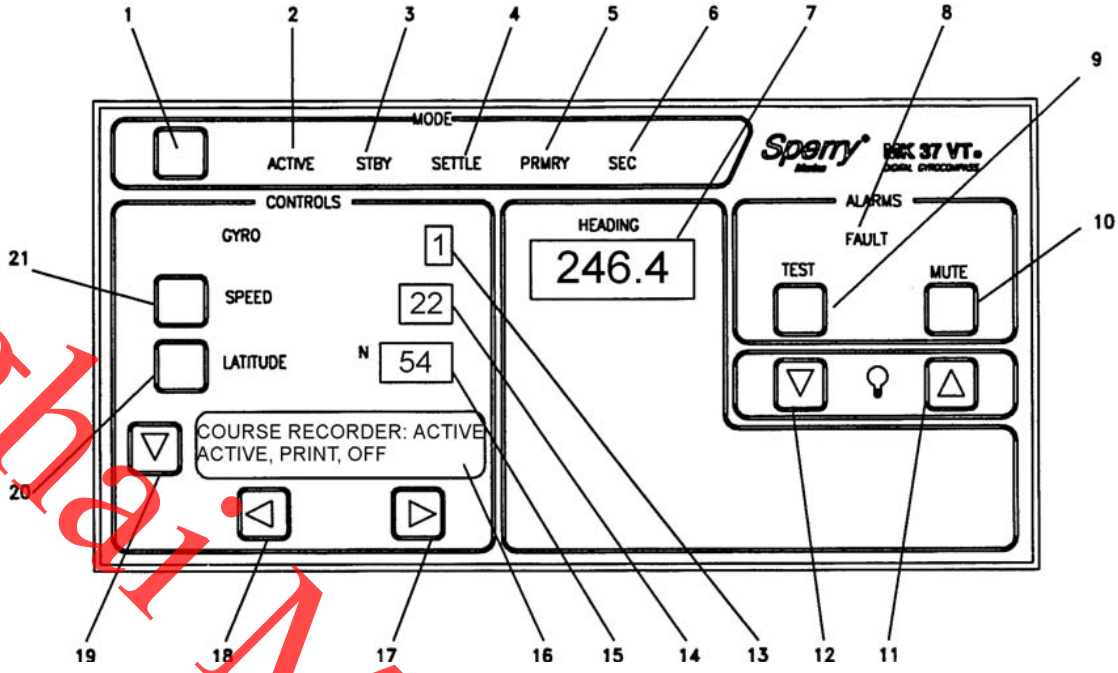

Figure 1.30 Sperry MK 37 VT control panel. (Reproduced courtesy of Litton Marine Systems.)

The Mode switch, number 1, is fixed when using a single system, the Active indicator lights and a figure 1 appear in window 13. Other Mode indicators include: 'STBY', showing when the gyrocompass is in a dual configuration and not supplying outputs; 'Settle', lights during compass start-up; 'Primary', lights to show that this is the primary compass of a dual system; and 'Sec', when it is the secondary unit.

Number 7 indicates the Heading display accurate to within 1/10th of a degree. Other displays are: number 14, speed display to the nearest knot; number 15, latitude to the nearest degree; and 16, the data display, used to display menu options and fault messages. Scroll buttons 17, 18 and 19 control this display. Other buttons functions are self-evident.

1.9.2 System description

Figure 1.31 shows, to the left of the CPU assembly, the gyrosphere with all its control function lines, and to the right of the CPU the Display and Control Panel and output data lines.

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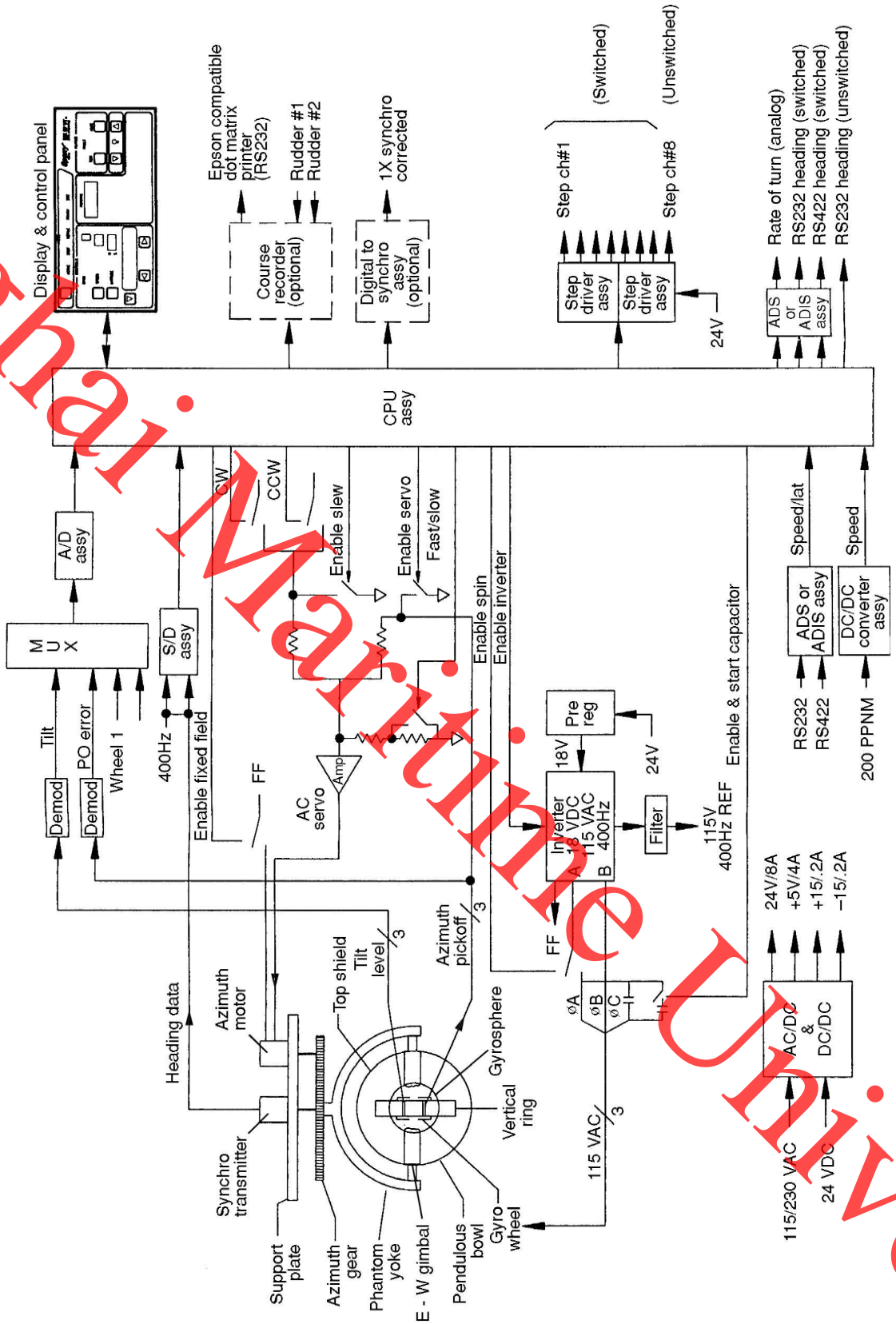

Figure 1.31 Overall functional block diagram. (Reproduced courtesy of Litton Marine Systems.)

The gyrosphere is supported by a phantom yoke and suspended below the main support plate. A 1-speed synchro transmitter is mounted to the support plate, close to the azimuth motor, and is geared to rotate the compass dial. The phantom yoke supports the east–west gimbal assembly through

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horizontal axis bearings. To permit unrestricted movement, electrical connections between the support plate and the phantom yoke are made by slip rings. The east–west gimbal assembly supports the vertical ring and horizontal axis bearings. See Figure 1.32.

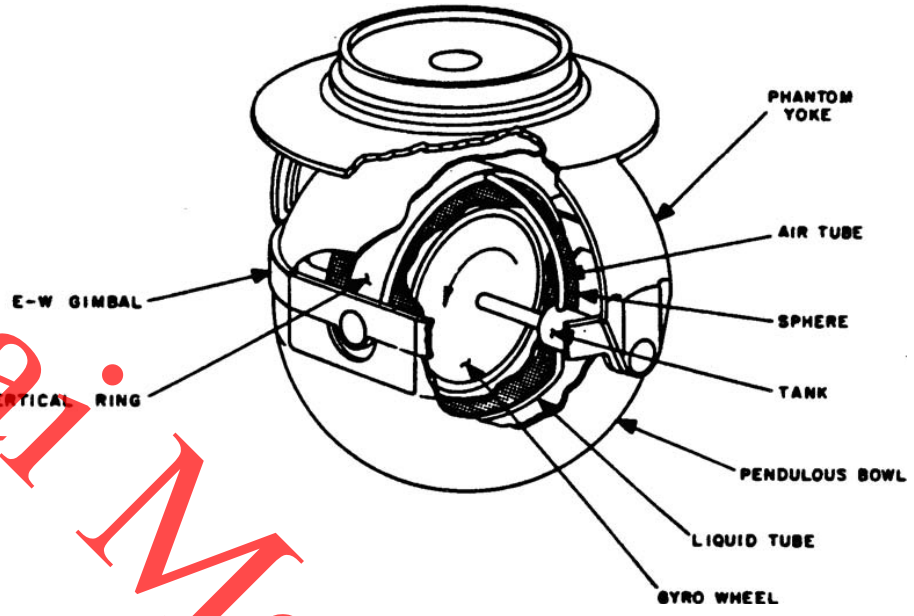

Figure 1.32 Ballistic system of the Sperry MK 37 VT gyrocompass.
(Reproduced courtesy of Litton Marine Systems.)

The gyrosphere

The gyrosphere is 6.5 inches in diameter and is pivoted about the vertical axis within the vertical ring, which in turn is pivoted about the horizontal axis in the east–west gimbal assembly. At operating temperature, the specific gravity of the sphere is the same as the liquid ballistic fluid in which it is immersed. Since the sphere is in neutral buoyancy, it exerts no load on the vertical bearings. Power to drive the gyro wheel is connected to the gyrosphere from the vertical ring through three spiral hairsprings with a fourth providing a ground connection.

The liquid ballistic assembly, also known as the control element because it is the component that makes the gyrosphere north-seeking, consists of two interconnected brass tanks partially filled with silicon oil. Small-bore tubing connects the tanks and restricts the free flow of fluid between them.

Because the time for fluid to flow from one tank to the other is long compared to the ship's roll period, roll acceleration errors are minimized.

Follow-up control

An azimuth pick-off signal, proportional to the azimuth movement of the vertical ring, is derived from an E-core sensor unit and coupled back to the servo control circuit and then to the azimuth motor mounted on the support plate. When an error signal is detected the azimuth motor drives the azimuth gear to cancel the signal.

Heading data from the synchronous transmitter is coupled to the synchro-to-digital converter (S/D ASSY) where it is converted to a 14-bit word before being applied to the CPU. The synchro heading data, 115V a.c., 400 Hz reference, 90 V line-to-line format, is uncorrected for ship's speed error and latitude error. Corrections for these errors are performed by the CPU using the data connected by the analogue, digital, isolated serial board (ADIS) from an RS-232 or RS-422 interface.

Interface data

Compass interfacing with external peripheral units is done using NMEA 0183 format along RS-232

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and RS-422 lines.

CPU assembly

The heart of the electronic control and processing system, the CPU, is a CMOS architecture arrangement communicating with the Display and Control Panel and producing the required outputs for peripheral equipment. Two step driver boards allow for eight remote heading repeaters to be connected. Output on each channel is a + 24 V d.c. line, a ground line and three data lines D1, D2 and D3. Each three-step data line shows a change in heading.

Scheduled maintenance and troubleshooting

The master compass is completely sealed and requires no internal maintenance. As with all computerbased equipment the Sperry MK 37 VT gyrocompass system possesses a built-in test system (BITE) to enable health checks and first line trouble shooting to be carried out. Figure 1.33 shows the trouble analysis chart for the Sperry MK 37 VT system. In addition to the health check automatically carried out at start-up, various indicators on the control panel warn of a system error or malfunction. Referring to the extensive information contained in the service manual it is possible to locate and in some cases remedy a fault.

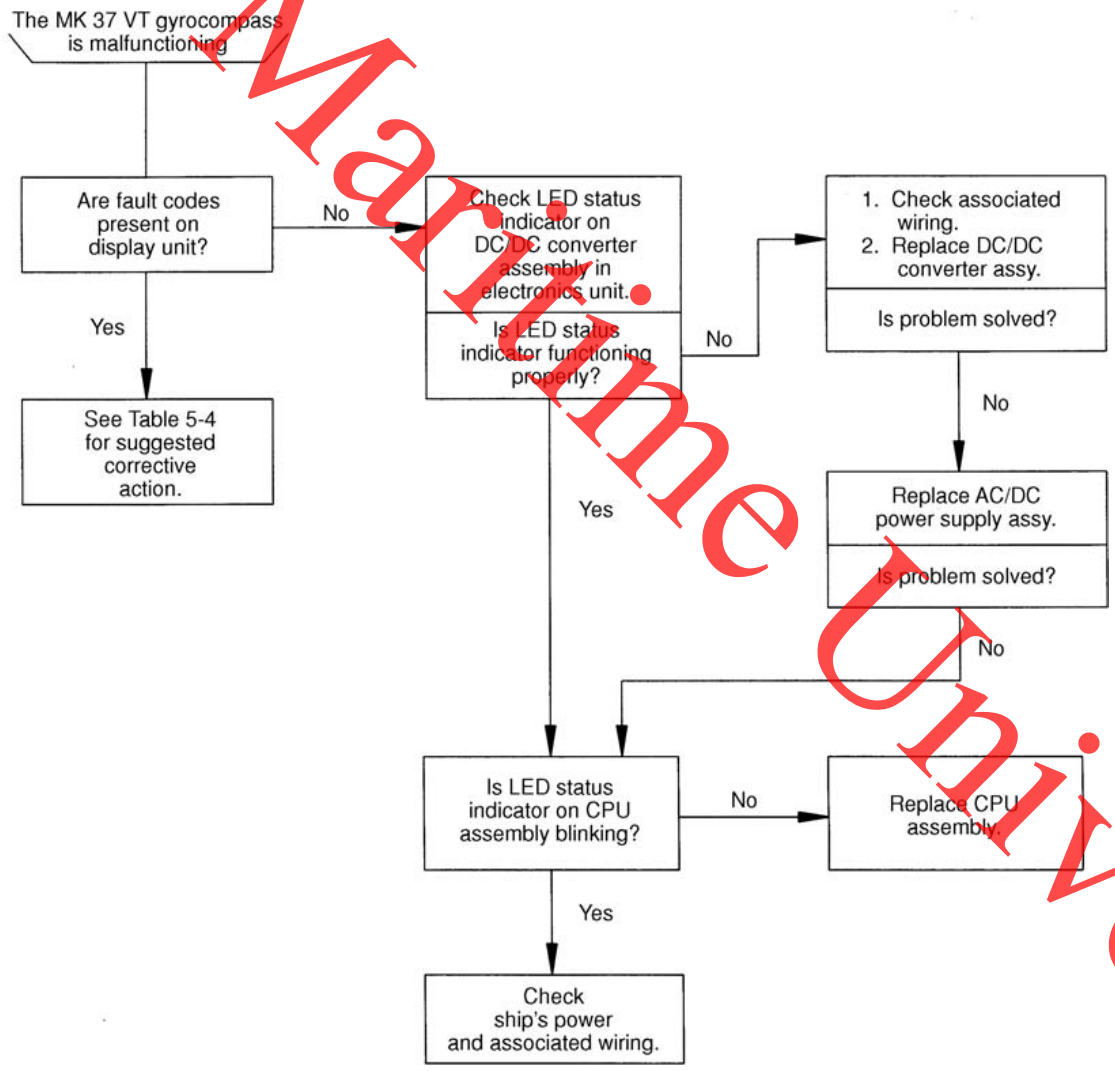
The MK 37 VT gyrocompass is malfunctioning
Are fault codes present on display unit?
No
Yes
See Table 5-4 for suggested corrective action.
Check LED status indicator on DC/DC converter assembly in electronics unit.
Is LED status indicator functioning properly?
No
1. Check associated wiring.
2. Replace DC/DC converter assy.
Is problem solved?
No
Replace AC/DC power supply assy.
Is problem solved?
No
Yes
Is LED status indicator on CPU assembly blinking?
No
Replace CPU assembly.
Yes
Check ship's power and associated wiring.

Figure 1.33 Sperry MK 37 VT digital gyrocompass trouble analysis chart.
(Reproduced courtesy of Litton Marine Systems.)

So far this description has only considered gyrocompass equipment using a top-heavy control

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mechanism. Many manufacturers prefer to use a bottom-heavy control system. One of the traditional manufacturers, S.G. Brown Ltd, provides some fine examples of bottom-heavy gyroscopic control.

1.10 A bottom-heavy control gyrocompass

Modern bottom-heavy controlled gyrocompasses tend to be sealed gyroscopic units with full computer control and electronic interfacing. For the purpose of system description, this early gyrocompass is a good example of bottom-heavy control used to settle and stabilize a compass.

The gyroscopic element, called the sensitive element, is contained within a pair of thin walled aluminium hemispheres joined as shown in Figure 1.34, to form the 'gyroball'. At the heart of this ball is a three-phase induction motor, the rotor of which protrudes through the central bobbin assembly but is able to rotate because of the high quality support bearings. At each end of the rotor shaft, a heavy rimmed gyro spinner is attached to provide the necessary angular momentum for gyroscopic action to be established. Rotational speed of the induction motor is approximately 12 000 rpm.

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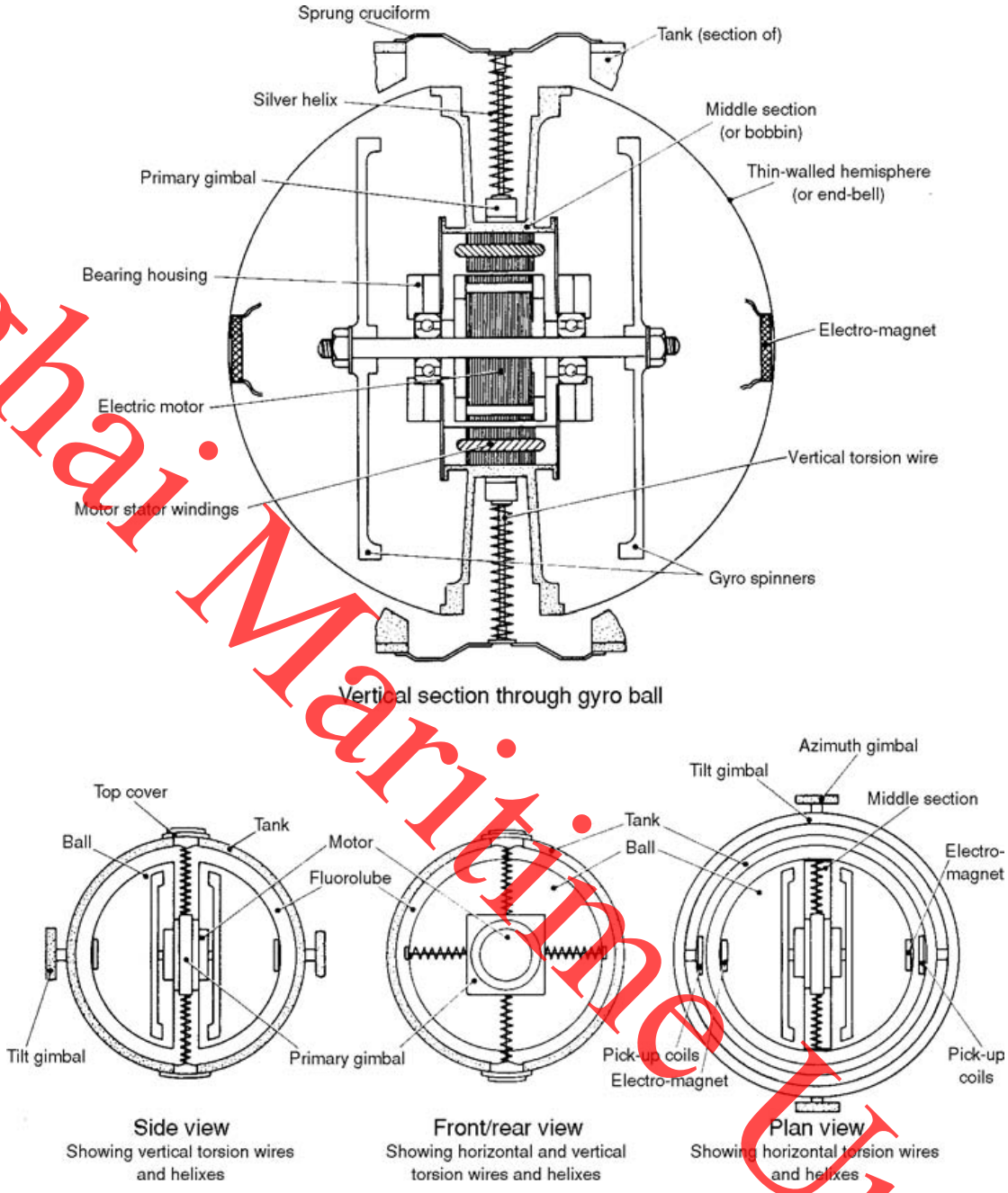

Figure 1.34 Arrangement of the gyroball. (Reproduced courtesy of S.G. Brown Ltd.)

The gyroball is centred within the tank by means of two vertical and two horizontal torsion wires forming virtually friction-free pivots. The torsion wires permit small controlling torques to be applied in both the vertical and the horizontal axes to cause precessions of the axes in both tilt and azimuth. In addition, the torsion wires are used to route electrical supplies to the motor. The gyroball assembly is totally immersed in a viscous fluid called halocarbon wax, the specific gravity of which gives the ball neutral buoyancy, at normal operating temperatures, so that no mass acts on the torsion wires.

The tank containing the gyroball sensitive element is further suspended in a secondary gimbal system, as shown in Figure 1.35, to permit free movement of the spin axis. This axis is now termed the 'free-swing axis' which under normal operating conditions is horizontal and in line with the local meridian. The secondary gimbal system also permits movement about the east–west axis. Each of the movable axes in the secondary gimbal system can be controlled by a servomotor, which in turn

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provides both tilt and azimuth control of the gyroball, via a network of feedback amplifiers.

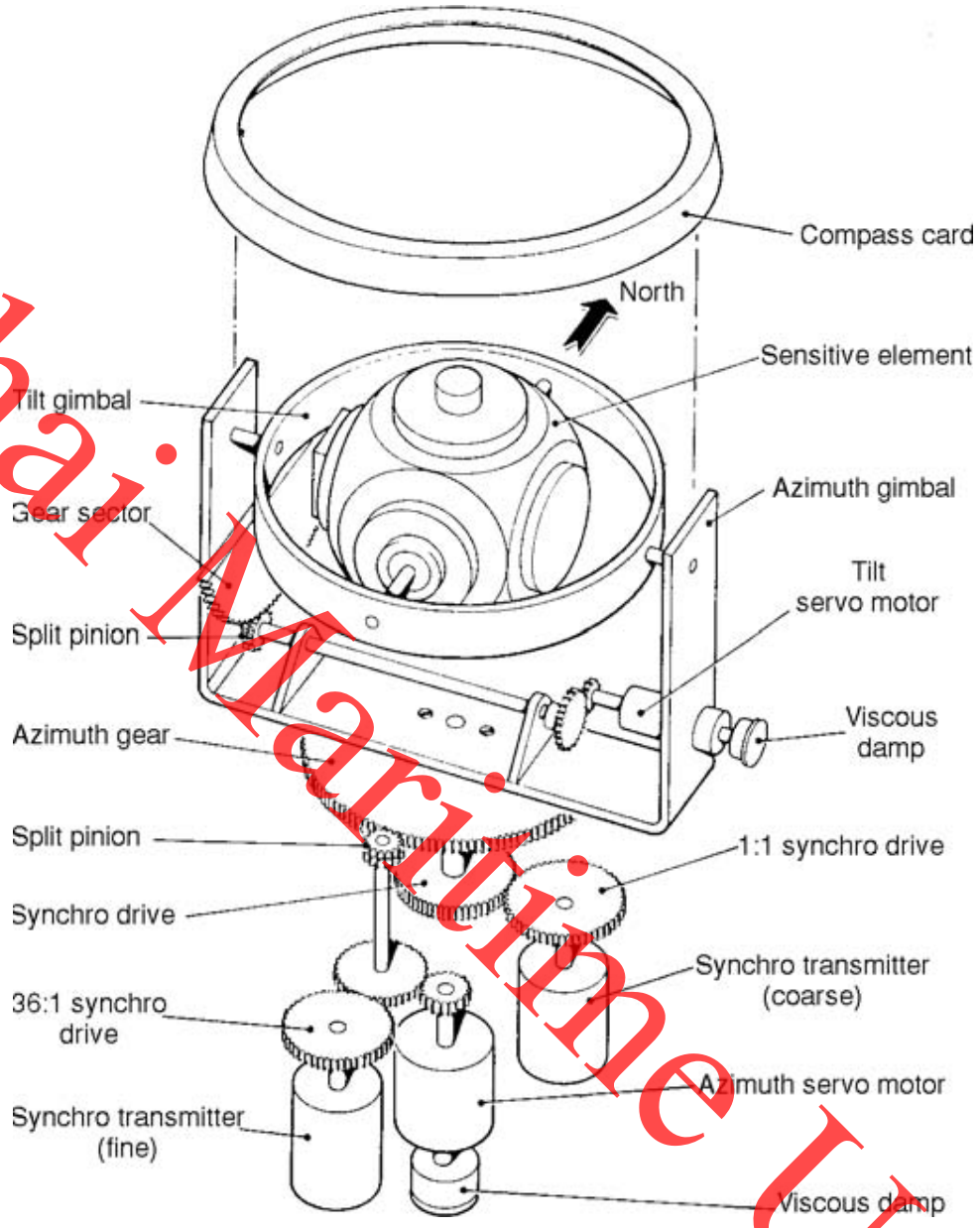

Figure 1.35 Schematics showing the arrangement of the secondary gimbals.

An electromagnetic pick-up system initiates the signal feedback system maintaining, via the secondary gimbals and servomotors, the gyro free-swing (spin) axis in alignment with the north-south axis of the tank. If there is no twist in the two pairs of torsion wires, and no spurious torques are present about the spin axis, no precession of the gyroball occurs and there will be no movement of the control servomotors. The gyro spin axis is in line with a magnet mounted in each hemisphere of the gyroball. Pick-up coils are mounted on the north/south ends of the containment tank and are arranged so that when the gyro-ball is in alignment with the tank, no output from the coils is produced. If any misalignment occurs, output voltages are produced that are proportional to the displacement in both tilt and azimuth. These small e.m.f.s are amplified and fed back as control voltages to re-align the axis by precession caused by moving the secondary gimbal system. The tiny voltages are used to drive the secondary gimbal servomotors in a direction to cancel the sensor pick-up voltages and so maintain the correct alignment of the gyroball within the tank.

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With a means of tank/gyroball alignment thus established, controlled precessions are produced. Referring to Figure 1.36, to precess the gyroball in azimuth only, an external signal is injected into the tilt amplifier. The null signal condition of the pick-up coils is now unbalanced and an output is produced and fed back to drive the tilt servomotor. This in turn drives the tilt secondary gimbal system to a position in which the tilt pick-up coil misalignment voltage is equal and opposite to the external voltage applied to the amplifier.

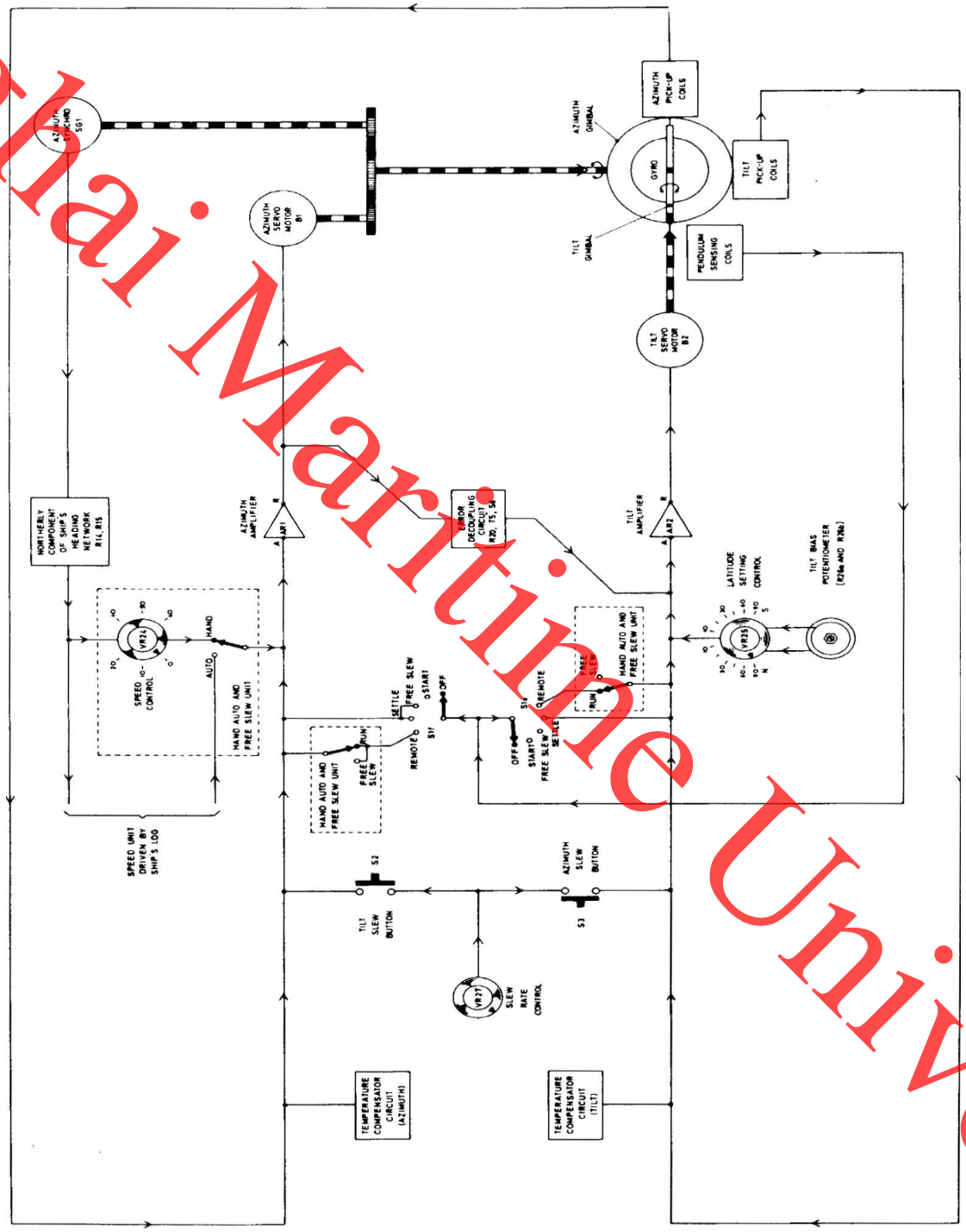

Figure 1.36 Compass circuits schematic. (Reproduced courtesy of S.G. Brown Ltd.)

The tilt servo feedback loop is now nulled, but with the tank and gyroball out of alignment in a tilt mode. A twist is thus produced of the horizontal torsion wires, creating a torque about the horizontal

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axis of the gyroball and causing it to precess in azimuth. As azimuth precession occurs, azimuth misalignment of the tank/gyroball also occurs but this is detected by the azimuth pick-up coils. The azimuth servomotor now drives the secondary gimbal to rotate the tank in azimuth to seek cancellation of the error signal. Since the azimuth secondary gimbal maintains a fixed position relative to the gyro spin axis in azimuth, a direct heading indication is produced on the compass card mounted on this gimbal.

Control of the sensitive element in tilt is done in a similar way. Therefore signals injected into the tilt and azimuth servo loops, having a sign and amplitude that produce the required precessional directions and rates, will achieve total control of the gyrocompass.

It is a relatively simple task to control the gyroball further by the introduction of additional signals because each of the feedback loops is essentially an electrical loop. One such signal is produced by the 'gravity sensor' or 'pendulum unit'. The pendulum unit replaces the liquid ballistic system, favoured by some manufacturers, to produce gravity control of the gyro element to make the compass north-seeking.

To produce a north-seeking action, the gyroscopic unit must detect movement about the east–west (horizontal) axis. The pendulum unit is therefore mounted to the west side of the tank, level with the centre line. It is an electrically operated system consisting of an 'E'-shaped laminated transformer core, fixed to the case, with a pendulum bob freely suspended by two flexible copper strips from the top of the assembly. The transformer (Figure 1.37) has series opposing wound coils on the outer 'E' sections and a single coil on the centre arm. The pendulum-bob centres on the middle arm of the 'E' core and is just clear of it. The whole assembly is contained in a viscous silicon liquid to damp the short-term horizontal oscillations caused by the vessel rolling.

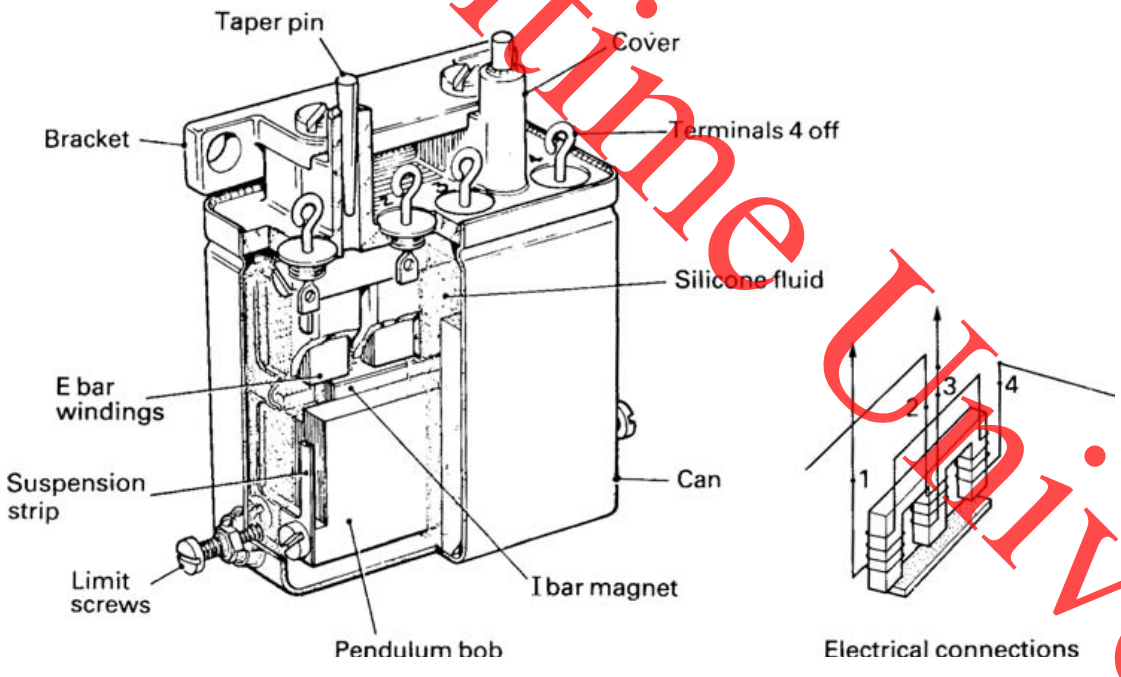

Figure 1.37 The pendulum assembly and its electrical connections.

(Reproduced courtesy S. G. Brown Ltd.)

Initially the bob will centre in the middle of the 'E' core, but if the gyro tank tilts, the bob will offset causing the normally equalized magnetic field to be unbalanced and produce a stronger field on the outer arm towards which it is offset. The result is that a tilt signal, of correct sense and amplitude, is produced. This signal is fed to the tilt and azimuth amplifiers as required.

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The output signal of the pendulum unit is also used to enable the gyro to settle in the meridian and become 'north settling'. A small carefully calibrated portion of the output signal is applied to the azimuth amplifier to cause azimuth misalignment of the gyro tank and hence a twist of the vertical torsion wires. The result is a tilt of the sensitive element, the direction of which depends on whether the gyro spin axis is north or south end up with respect to the horizontal. The amplitude of the pendulum signal fed to the azimuth amplifier will determine the settling period of the gyro, which for this compass is 40 min.

Loop feedback versatility is again made use of by applying signals in order to achieve the necessary corrections for latitude and speed errors. The injected signals result in the required precessional rates in azimuth, for latitude correction and in tilt, for speed correction.

1.10.1 Speed correction

A signal that is proportional to the ship's speed and the cosine of the ship's course, is coupled back to the azimuth amplifier to cause the gyroball to tilt in opposition to the apparent tilt caused by the northerly or southerly component of the ship's speed. The signal will therefore be maximum in amplitude when the course is due north or south, but will be of opposite sense. If the course is due east or west no correction is necessary. The system uses a 1:1 ratio azimuth synchronous transmitter SG1, which is mechanically driven by the azimuth servomotor gearing, and a balanced star connected resistor network as shown in Figure 1.38.

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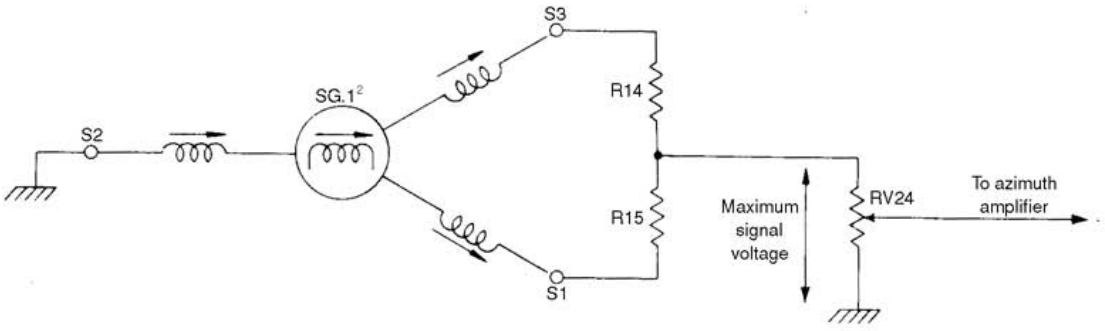
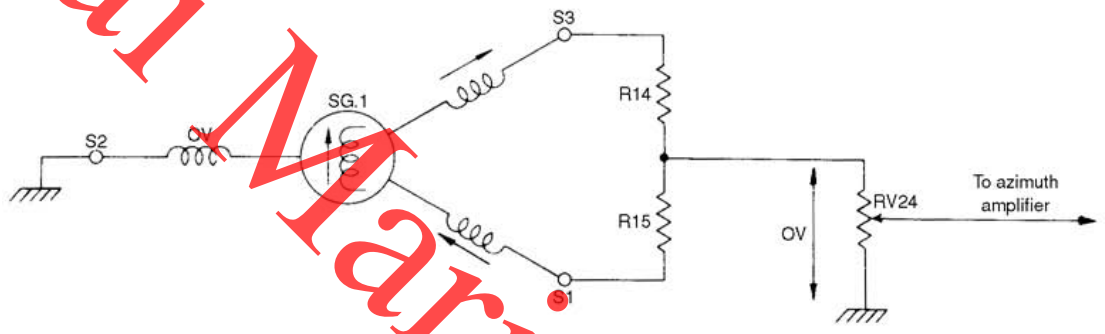
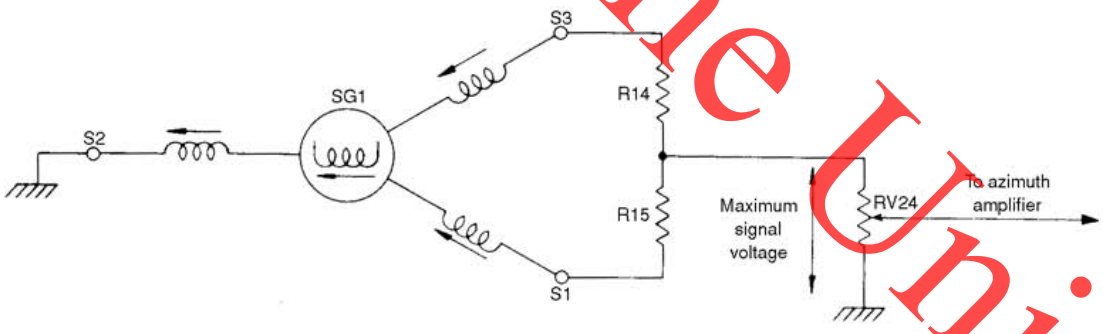


(a) Ship sailing north



(b) Ship sailing east



(c) Ship sailing south

Note:-
Arrows denote instantaneous current flow

Figure 1.38 Signal output of synchro SG1 for different headings.
(Reproduced courtesy S.G. Brown Ltd.)

Alternatively an external signal derived from the ship's speed log may be used. In Figure 1.38 the error for a ship sailing due north is maximum and therefore the feedback signal produced across RV24, by the currents flowing through SG1, S1 and S2 coils, will be maximum. A portion of this signal, dependent upon the speed setting of RV24, is fed to the azimuth amplifier to produce a tilt of the

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gyroball. For a course due south, the signal is again maximum, but is of opposite phase to the northerly signal. This will cause an opposite tilt of the gyroball to be produced. With the ship sailing due east, the synchronous transmitter SG1 is in a position which will produce a zero signal across RV24 and no correction signal is applied to the azimuth amplifier irrespective of the speed setting of RV24. Any intermediate setting of SG1 will produce a corresponding correction signal to be developed across RV24.

1.10.2 Latitude correction

The latitude correction circuit provides a signal, proportional to the sine of the vessel's latitude, to cause the gyroball to precess in azimuth at a rate equal and opposite to the apparent drift caused by the rotation of the earth. This signal will be zero at the equator and maximum at the poles. It must also be of opposite phase for north or south latitudes. VR25 (see Figure 1.36), the latitude potentiometer, derives its signal from the 24V centre-tapped secondary winding of a transformer, and therefore has signals of opposite phase at either end. This control sets the amplitude of the correction signal and is manually adjusted.

1.10.3 Temperature compensation

Both the vertical and horizontal torsion wires may twist with a change in ambient temperature. A corrective signal is produced in each of the tilt and azimuth temperature compensation circuits to counteract any precession of the gyroball caused by a change in temperature. The corrective signals are produced in the compensation circuits and connected to the tilt and azimuth amplifiers in such a way that both signal amplitude and sense will cause torques to be produced which are equal and opposite to those produced by twisting of the torsion wires. The effect of ambient temperature on the torsion wires is therefore cancelled.

1.10.4 Error decoupling circuit

The accuracy of a gyrocompass can be seriously affected by violent movement of the vessel, particularly heavy rolling caused by severe storms and rapid manoeuvring. A carefully calibrated error signal is derived from the output of the azimuth amplifier (which will be present due to misalignment of the tank and gyro spin axis during such conditions) and applied to the tilt amplifier to control the tilt gimbals. The system will provide partial and adequate compensation for errors that arise due to violent rolling conditions. The correction system is more than adequate for fittings on Merchant Navy vessels that are rarely subjected to rapid manoeuvres.

1.10.5 Slew rate

The purpose of the slew rate control VR27 (see Figure 1.36) is to rapidly level and orientate the gyro during the start-up procedure. The potentiometer VR27 is connected across the 24 V centre-tapped secondary winding of a transformer and is therefore able to produce an output of opposite phase and varying amplitude. The signal voltage level set by VR27 may be applied to the input of either the azimuth or tilt amplifiers separately by the use of push buttons. The buttons are interconnected in such a way that the signal cannot be applied to both amplifiers at the same time.

If the output of VR27 is firstly applied to the tilt servo amplifier (by pressing the azimuth slew button) the gyro will precess towards the meridian. If the tilt slew button is now pressed, the gyro will be levelled by applying the output of VR27 to the azimuth servomotor. The slew rate control VR27 adjusts the rate at which the gyro precesses and not the extent of precession, which is a function of time. It is essential that this control is centred before either slew button is pressed, otherwise a violent kick of the gyro ball will occur in one direction making compass alignment more difficult to achieve. The selector switch S1 must be in the 'free slew' position during this operation.

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1.11 Starting a gyrocompass

As has been previously stated, from start-up a gyrocompass needs time to settle on the meridian. The time taken depends upon the make, model and the geographic location of the compass, but in general it is between one and several hours. The duration also depends upon whether the gyro wheel is already rotating or not. If the compass has been switched off, it will take much longer to bring the compass into use. Inputting the ship's heading to reduce the initial error factor can reduce the time period. As an example, the following section considers the start-up procedure for the Sperry MK37 VT Digital Gyrocompass.

At power-up and prior to entering the settle mode, the system performs the automatic 'bite' procedure to determine if the equipment is operating within specified parameters. The CPU also initializes the system hardware and communication channels. During this procedure the gyro wheel is checked for movement. If it is stationary, the system ops for a cold start, if it is rotating a hot start is programmed. During a cold start, if no heading data is input to the system when requested, the gyrocompass selects Automatic.

1.11.1 Cold starting the compass

After an initial period, during which the bite is active, the following sequence is initiated and the settle indicator lamp will be lit.

- Two bleeps prompt the operator for a heading input. If heading data is not entered within 5 min, the gyro switches to an 'auto level' process.
- Assuming heading data has been input, the yoke will be offset based on this data. It will be slewed from the meridian, either clockwise or anticlockwise.
- The gyrowheel is brought up to speed within 14 min.
- The yoke is slewed back and forth to level the ballistic. This action takes about 4 min.
- Again assuming heading data has been input, the gyrocompass will settle within 1 h and the settle indicator lamp goes out. If no heading data was entered, the compass will automatically settle within 5 h.

Other inputs to the gyrocompass are as follows.

- Heading: in the range 0 to 359°. If the entered heading is in error by more than 20° from the true heading, the compass takes 5 h to settle.
- Initialize and Synchronize Step Repeaters. An operator selects a repeater and when requested uses the keypad's left or right arrow switches to scroll the display to the repeater's current position. After 10 s the system steps the repeater to the compass heading. It is essential to repeat and double check this procedure because there must be no alignment errors in a repeater system.
- Speed Input. Using the left or right arrow keys, an operator inputs a speed in the range 0–70 knots.
- Latitude Input. Using the arrow keys, an operator inputs latitude in degrees north or south of the equator.

1.12 Compass repeaters

Remote analogue compass repeaters are simply mechanized compass cards driven either by a stepper motor or a synchro bearing transmission system. Digital heading displays can also be produced by

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digitizing the stepper 'grey code' waveform before applying it to a suitable decoding system. This section deals with the most popular bearing transmission systems.

1.12.1 Stepper systems

Figure 1.39 shows a mechanical switching stepper system which, because its robustness, is still found on many merchant ships for bearing transmission to remote repeaters. The rotor of the transmitter is geared to the azimuth ring gearing of the master compass. The transmitter is a multi-contact rotary switch that completes the circuit for current to flow through the appropriate repeater motor coils. The transmitter rotor has two rotating arms spaced at 165° to each other. Each rotor arm makes contact with copper segments arranged in four groups of three, with each segment being wired to its corresponding number in the other three groups.

The gear ratio of transmitter rotor to azimuth gear is 180:1. Therefore:

180 rev = 360°

1 rev = 2°

12 seg = 2°

1 seg = 2/12° or 10 min of arc

The rotating arms make 12 steps per revolution. Because of the 180:1 gear reduction, each step therefore corresponds to 1/6th of a degree or 10 min of arc on the compass card.

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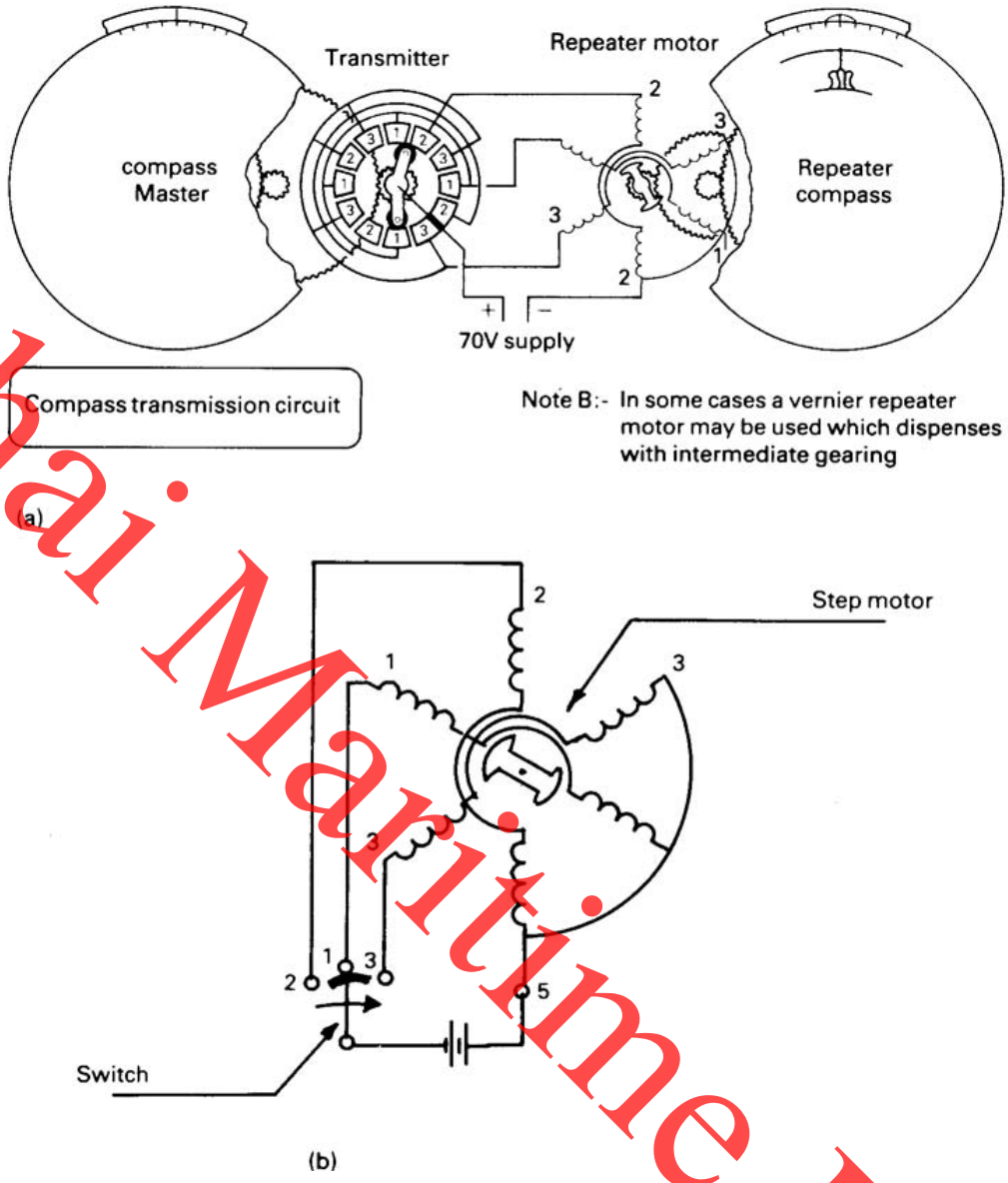

Figure 1.39 Stepper repeating system. (a) Early mechanical switching system; (b) diagrammatic representation of a simple step motor receiver. (Reproduced courtesy of Sperry Ltd.)

A simplified step by step receiver is shown in Figure 1.39(b). Three pairs of coils are wound, and located at 60° intervals on the stator assembly of the receiver. The rotor is centrally located and capable of rotating through 360°. With the switch in the position shown, current flows through the series connected coils (1) and, under the influence of the magnetic field produced, the rotor takes up the position shown. As the switch moves to position 3, its make-before-break action causes current to flow through both coils 1 and 3 and the rotor moves to a position midway between the coils, due east–west. The next movement of the switch energizes coil 3 only causing the rotor to line up with this coil.

In this way the rotor is caused to rotate one revolution in 12 steps. The construction details of a step motor are given in Figure 1.40.

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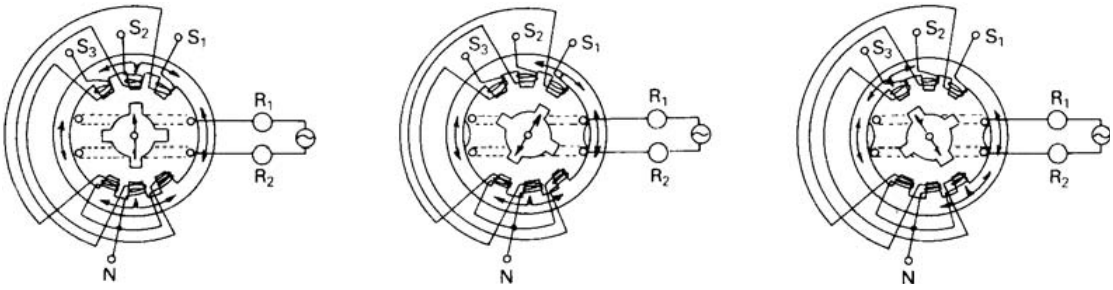

Figure 1.40 Construction details of a step motor.

A stepper system such as this may also be used as part of a 'direct digital control' (d.d.c.) system in which signals are generated digitally to control movement of the repeater. Such a stepper system uses a cyclic binary code or gray code for its operation. The gray code is easily produced using shaft or disc encoders geared to the compass azimuth gearing.

1.12.2 Synchro systems

A synchro is a device that uses the basic principle of a single-phase transformer with magnetic coupling between a rotating primary (rotor) and a number of secondaries (stators). For the purpose of this description three secondaries are located at 120° intervals on the stator. The rotor may be rotated through 360° within the laminated stator assembly holding the three secondary windings. The primary coil is energized by a low frequency a.c. applied via slip rings located on the main shaft. The magnitude and phase of the secondary induced e.m.f.s is dependent upon the relative position of the rotor in relation to the stator windings.

Figure 1.41 shows a synchro repeater system using the basic 'synchro error detecting' method of operation common to many control applications. The rotor of the synchro transmitter is reduction geared to the azimuth ring of the gyrocompass. A reference low frequency a.c. supply to the transmitter rotor coil couples with the three secondaries to produce e.m.f.s which cause current to flow around the three circuits. Each current flow produces a magnetic field around the corresponding receiver secondary and a resultant error signal is induced in the receiver rotor coil. No error signal is produced if the system is in the synchronous state with the transmitter and the receiver rotors at 90° to each other.

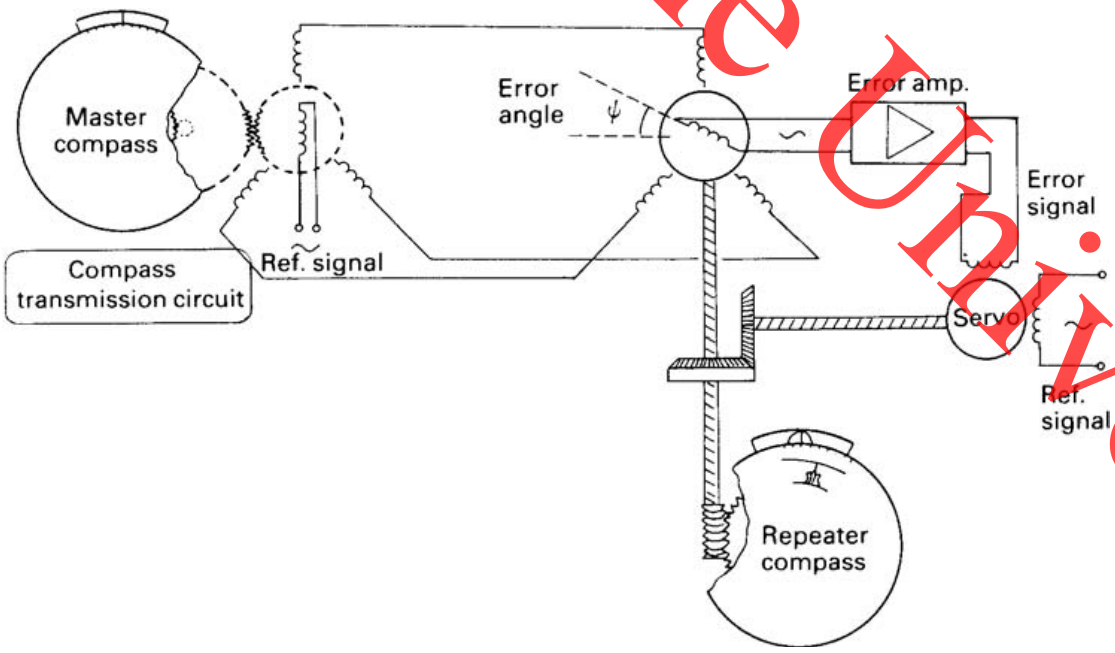

Figure 1.41 A synchro bearing transmission system.

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The error signal present, when the rotors are not synchronized, is directly proportional to the error angle (ψ) existing between the horizontal and the plane of the rotor. This error signal is amplified to the level required to drive a servo to turn the compass card. Also mechanically coupled to the servo shaft is the receiver rotor that turns to cancel the error signal as part of a mechanical negative feedback arrangement. The receiver rotor will always therefore line up (at 90°) with the transmitter rotor to produce the synchronous state.

1.13 Glossary

Angular momentum In the case of a gyrowheel, this is the product of its linear momentum and the radius of the rotor.

Ballistic pots Containers of viscous liquid to add damping to a gyrocompass.

BITE Built-in test equipment. Automatic or manually commanding equipment test circuits.

Compass repeaters Remote display of compass information.

Controlled gyroscope One in which the movement caused by earth rotation is controlled.

Drift The apparent movement in azimuth of a gyroscope due to earth rotation.

Dynamic errors Errors caused by the angular motion of the vessel during heavy weather or manoeuvring.

Flux gate The electrical sensing unit of a magnetic compass.

Free gyroscope A gyroscope with a spin axis fixed by inertia to some celestial reference point and not to a terrestrial point. Not suitable as a gyrocompass.

Follow-up A system enabling control of the gyro when it is fitted on board a moving platform.

Gyroscope A perfectly balanced wheel that is able to spin at high speed symmetrically about an axis.

Gyroscopic inertia A gyroscope rotor maintains the direction of its plane of rotation unless an external force of sufficient amplitude to overcome inertia is applied to alter that direction.

Latitude error A constant value error the magnitude of which is directly proportional to earth rotation at any given latitude.

Linear momentum The product of mass and velocity.

Manoeuvring error An error caused by a vessel's rapid changes of speed and/or heading.

North-seeking gyro One which is partly controlled and as a consequence will seek to locate north but will not settle. Further control is required to convert this type of gyro into a compass.

North-settling gyro One which is fully controlled and will settle to point north.

Precession Movement at 90° from the applied force. If a force is applied to a spinning rotor by moving one end of its axle, the gyroscope is displaced at an angle of 90° from the applied force.

Rolling error As the name suggests, this error is caused by a vessel rolling. The error cancels when the ship is steaming north or south and is maximum when following an east/west course.

Settling time The period taken for a gyrocompass to settle on the meridian from startup.

Slew rate control A control setting an electrical input to rapidly level and orientate the gyro during start-up.

Stepper systems A step motor compass repeater circuit.

Synch. systems A synchronous motor compass repeater circuit.

Tilt By virtual of precession, the earth's rotation causes the spin axis to tilt upwards to an angle dependent upon its position in latitude.

Transmission error An error existing between the master compass and any repeaters.

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1.14 Summary

- There are three axes in which a gyroscope is free to move: the spin axis, the horizontal axis and the vertical axis.
- In a free gyroscope none of the three axes is restricted.
- A free gyroscope is subject to the laws of physics, the most important of which, when considering gyrocompass technology, is inertia.
- Precession is the term used to describe the movement of the axle of a gyroscope under the influence of an external force. Movement of the axle will be at 90° to the applied force.
- Tilt is the amount by which the axle tilts because of the gyroscope's position in latitude.
- Azimuth drift is the amount by which the axle drifts due to the earth's rotation.
- A controlled gyroscope is one with its freedoms restricted.
- A north-seeking gyroscope is a controlled gyro that never settles pointing north.
- A north-settling gyroscope is a damped controlled gyro that does settle on the meridian.
- Bottom- and top-heavy controls are methods used for settling a north-seeking gyroscope.
- A gyrocompass fitted on board a ship is affected by dynamic errors. They are rolling error, manoeuvring error, speed and course error and latitude or damping error. All these errors are predictable and controllable.
- When starting from cold, gyrocompasses require time to settle on the meridian. A settling time period of 75 min is typical.
- Stepper systems are transmission devices that relay the bearing on the master compass to remote repeaters.

1.15 Revision questions

1 Describe what you understand by the term gyroscopic inertia?
2 What do you understand by the term precession when applied to a gyrocompass?
3 Why is a free gyroscope of no use for navigation purposes?
4 How is earth's gravity used to turn a controlled gyroscope into a north-seeking gyroscope?
5 How is a north-seeking gyroscope made to settle on the meridian and indicate north?
6 When first switched on a gyrocompass has a long settling period, in some cases approaching 75 min. Why is this?
7 Explain the terms gyro-tilt and gyro-drift.
8 How is a gyrocompass stabilized in azimuth?
9 What is rolling error and how may its effects be minimized?
10 Why do gyrocompass units incorporate some form of latitude correction adjustment?
11 What effect does an alteration of a ship's course have on a gyrocompass?
12 What are static errors in a gyrocompass system?
13 When would you use the slew rate control on a gyrocompass unit?
14 Why is temperature compensation critical in a gyrocompass?
15 What is a compass follow-up system?
16 What is a compass repeater system?

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Chapter 2 The Ship's Echosounder

2.1 Introduction

Sonar (*so*und *n*avigation *a*nd *r*anging) is the acronym identifying those systems that rely for their operation on the transmission and reception of acoustic energy in water. The term is widely used to identify all modern systems that propagate acoustic or electromagnetic energy into seawater to determine a vessel's speed or the depth of water under the keel. This book is not concerned with those specialized sonar techniques that are used for locating submerged objects, either fish or submarines. A navigator in the Merchant Navy is interested only in the depth of the water beneath the vessel, an indication of the speed of his ship and the distance run. See Chapter 3 for a description of speed logging equipment. The first section of this chapter deals with the characteristics and problems that arise from the need to propagate energy in seawater.

2.2 The characteristics of sound in seawater

Before considering the problems of transmitting and receiving acoustic energy in seawater, the effects of the environment must be understood. Sonar systems rely on the accurate measurement of reflected frequency or, in the case of depth sounders, a precise measurement of time and both these parameters are affected by the often unpredictable ocean environment. These effects can be summarized as follows.

- Attenuation. A variable factor related to the transmitted power, the frequency of transmission, salinity of the seawater and the reflective consistency of the ocean floor.
- Salinity of seawater. A variable factor affecting both the velocity of the acoustic wave and its attenuation.
- Velocity of sound in salt water. This is another variable parameter. Acoustic wave velocity is precisely 1505 ms^{-1} at 15°C and atmospheric pressure, but most echo-sounding equipment is calibrated at 1500 ms^{-1}.Reflective surface of the seabed. The amplitude of the reflected energy varies with the consistency of the ocean floor.
- Noise. Either inherent noise or that produced by one's own transmission causes the signal-to-noise ratio to degrade, and thus weak echo signals may be lost in noise.

Two additional factors should be considered.

- Frequency of transmission. This will vary with the system, i.e. depth sounding or Doppler speed log.
- Angle of incidence of the propagated beam. The closer the angle to vertical the greater will be the energy reflected by the seabed.

2.2.1 Attenuation and choice of frequency

The frequency of the acoustic energy transmitted in a sonar system is of prime importance. To achieve a narrow directive beam of energy, the radiating transducer is normally large in relation to the wavelength of the signal. Therefore, in order to produce a reasonably sized transducer emitting a

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narrow beam, a high transmission frequency needs to be used. The high frequency will also improve the signal-to-noise ratio in the system because ambient noise occurs at the lower end of the frequency spectrum. Unfortunately the higher the frequency used the greater will be the attenuation as shown in Figure 2.1.

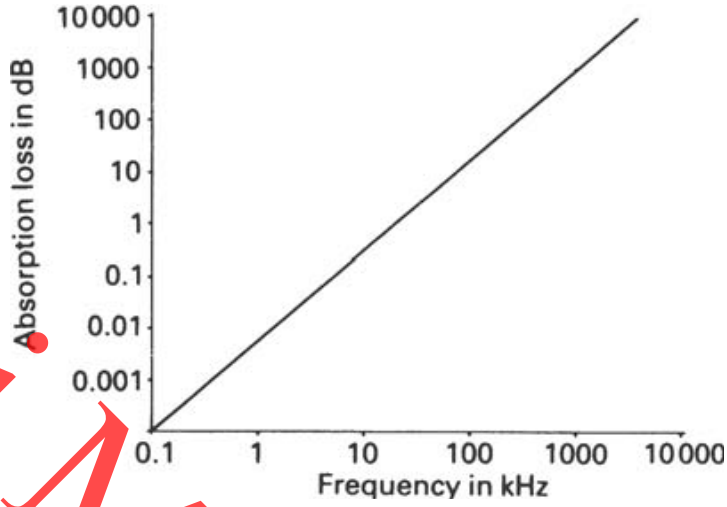

Figure 2.1 A linear graph produced by plotting absorption loss against frequency. Salinity of the seawater is 3.4% at 15°C.

The choice of transmission frequency is therefore a compromise between transducer size, freedom from noise, and minimal attenuation. Frequencies between 15 and 60 kHz are typical for depth sounders fitted in large vessels. A high power is transmitted from a large magnetostrictive transducer to indicate great depths with low attenuation. Small light craft use depth sounders that transmit in the band 200–400 kHz. This enables compact electrostrictive or ceramic transducers to be used on a boat where space is limited. Speed logs use frequencies in the range 300 kHz to 1 MHz depending upon their design and are not strictly sonar devices in the true definition of the sense.

Beam spreading

Transmission beam diverging or spreading is independent of fixed parameters, such as frequency, but depends upon distance between the transducer and the seabed. The greater the depth, the more the beam spreads, resulting in a drop in returned energy.

Temperature

Water temperature also affects absorption. As temperature decreases, attenuation decreases. The effect of temperature change is small and in most cases can be ignored, although modern sonar equipment is usually fitted with a temperature sensor to provide corrective data to the processor.

Consistency of the seabed

The reflective property of the seabed changes with its consistency. The main types of seabed and the attenuation which they cause are listed in Table 2.1. The measurements were made with an echo sounder transmitting 24 kHz from a magnetostrictive transducer.

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Table 2.1 Sea bed consistency and attenuation

Consistency	*Attenuation (dB)*
Soft mud	15
Mud/sand	9
Sand/mud	6
Sand	3
Stone/rock	1

These figures are typical and are quoted as a guideline only. In practice sufficient transmitted power will overcome these losses.

2.2.2 Salinity, pressure and the velocity of the acoustic wave

Since a depth sounder operates by precisely calculating the time taken for a pulse of energy to travel to the ocean floor and return, any variation in the velocity of the acoustic wave from the accepted calibrated speed of 1500 ms–1 will produce an error in the indicated depth. The speed of acoustic waves in seawater varies with temperature, pressure and salinity. Figure 2.2 illustrates the speed variation caused by changes in the salinity of seawater.

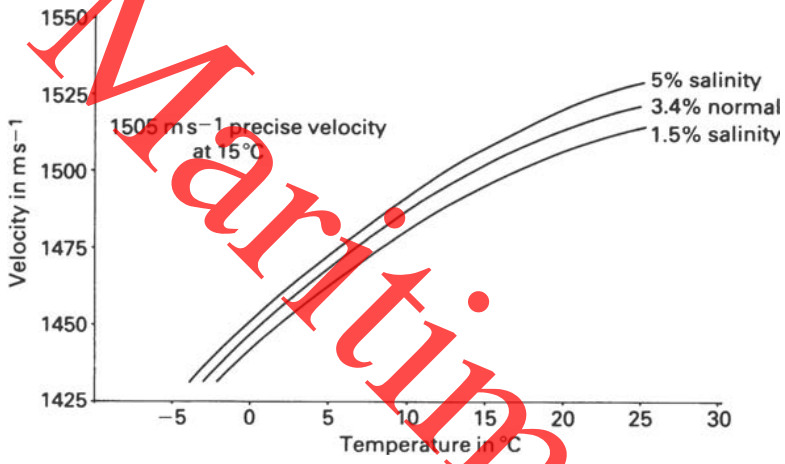

Figure 2.2 Graph showing that the velocity of acoustic energy is affected by both the temperature and the salinity of seawater.

Ocean water salinity is approximately 3.4% but it does vary extensively throughout the world. As salinity increases, sonar wave velocity increases producing a shallower depth indication, although in practice errors due to salinity changes would not be greater than 0.5%. The error can be ignored except when the vessel transfers from seawater to fresh water, when the indicated depth will be approximately 3% greater than the actual depth. The variation of speed with pressure or depth is indicated by the graph in Figure 2.3.

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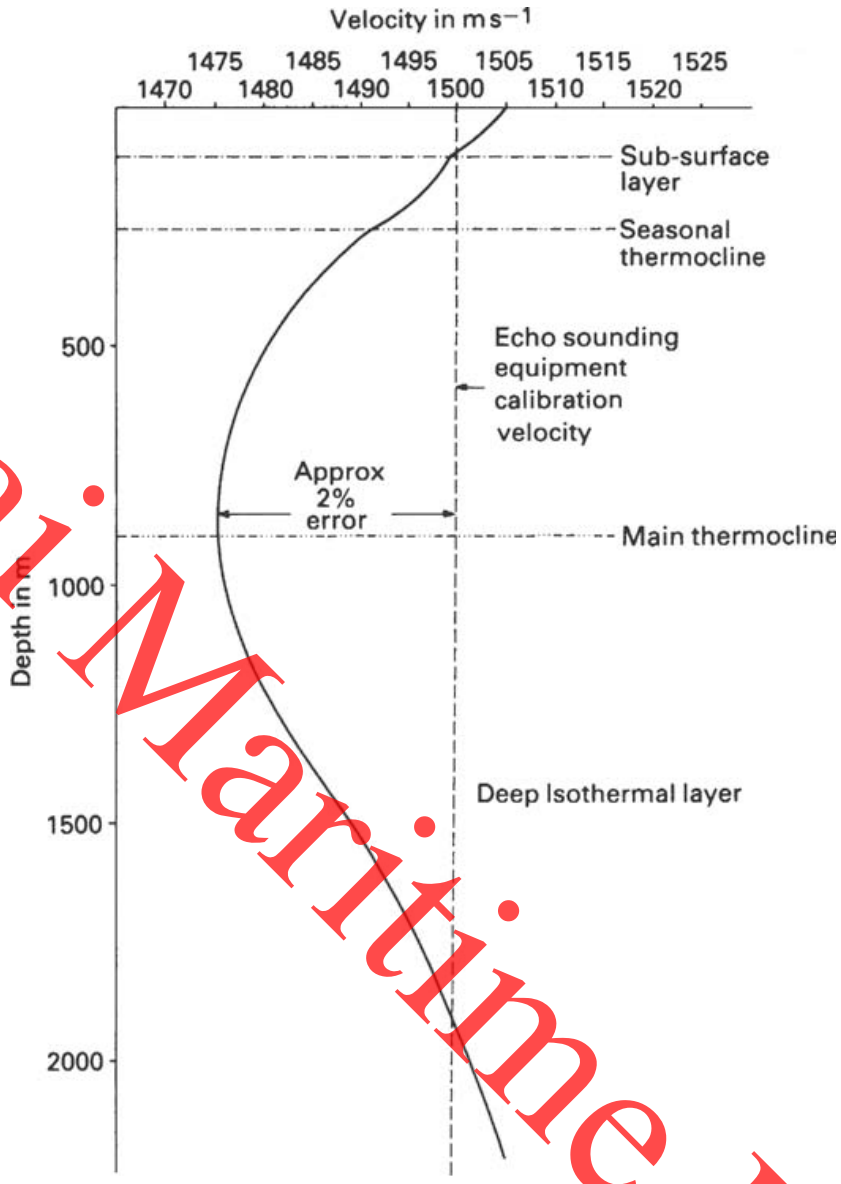

Figure 2.3 Variation of the velocity of acoustic waves with pressure.

It can readily be seen that the change is slight, and is normally only compensated for in apparatus fitted on survey vessels. Seasonal changes affect the level of the thermocline and thus there is a small annual velocity variation. However, this can usually be ignored.

2.2.3 Noise

Noise present in the ocean adversely affects the performance of sonar equipment. Water noise has two main causes.

- The steady ambient noise caused by natural phenomena.
- Variable noise caused by the movement of shipping and the scattering of one's own transmitted signal (reverberation).

Ambient noise

Figure 2.4 shows that the amplitude of the ambient noise remains constant as range increases, whereas both the echo amplitude and the level of reverberation noise decrease linearly with range. Because of beam spreading, scattering of the signal increases and reverberation noise amplitude falls more slowly than the echo signal amplitude.

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Ambient noise possesses different characteristics at different frequencies and varies with natural conditions such as rainstorms. Rain hitting the surface of the sea can cause a 10-fold increase in the noise level at the low frequency (approx. 10 kHz) end of the spectrum. Low frequency noise is also increased, particularly in shallow water, by storms or heavy surf. Biological sounds produced by some forms of aquatic life are also detectable, but only by the more sensitive types of equipment.

The steady amplitude of ambient noise produced by these and other factors affects the signal-to-noise ratio of the received signal and can in some cases lead to a loss of the returned echo. Signal-to-noise ratio can be improved by transmitting more power. This may be done by increasing the pulse repetition rate or increasing the amplitude or duration of the pulse. Unfortunately such an increase, which improves signal-to-noise ratio, leads to an increase in the amplitude of reverberation noise.

Ambient noise is produced in the lower end of the frequency spectrum. By using a slightly higher transmitter frequency and a limited bandwidth receiver it is possible to reduce significantly the effects of ambient noise.

Reverberation noise

Reverberation noise is the term used to describe noise created and affected by one's own transmission. The noise is caused by a 'back scattering' of the transmitted signal. It differs from ambient noise in the following ways.

- Its amplitude is directly proportional to the transmitted signal.
- Its amplitude is inversely proportional to the distance from the target.
- Its frequency is the same as that of the transmitted signal.

The signal-to-noise ratio cannot be improved by increasing transmitter power because reverberation noise is directly proportional to the power in the transmitted wave. Also it cannot be attenuated by improving receiver selectivity because the noise is at the same frequency as the transmitted wave.

Furthermore reverberation noise increases with range because of increasing beamwidth. The area covered by the wavefront progressively increases, causing a larger area from which back scattering will occur. This means that reverberation noise does not decrease in amplitude as rapidly as the transmitted signal. Ultimately, therefore, reverberation noise amplitude will exceed the signal noise amplitude, as shown in Figure 2.4, and the echo will be lost. The amplitude of both the echo and reverberation noise decreases linearly with range. However, because of beam spreading, back scattering increases and reverberation noise amplitude falls more slowly than the echo signal amplitude. Three totally different 'scattering' sources produce reverberation noise.

- Surface reverberation. As the name suggests, this is caused by the surface of the ocean and is particularly troublesome during rough weather conditions when the surface is turbulent.
- Volume reverberation. This is the interference caused by beam scattering due to suspended matter in the ocean. Marine life, prevalent at depths between 200 and 750 m, is the main cause of this type of interference.
- Bottom reverberation. This depends upon the nature of the seabed. Solid seabeds, such as hard rock, will produce greater scattering of the beam than silt or sandy seabeds. Beam scattering caused by a solid seabed is particularly troublesome in fish finding systems because targets close to the seabed can be lost in the scatter.

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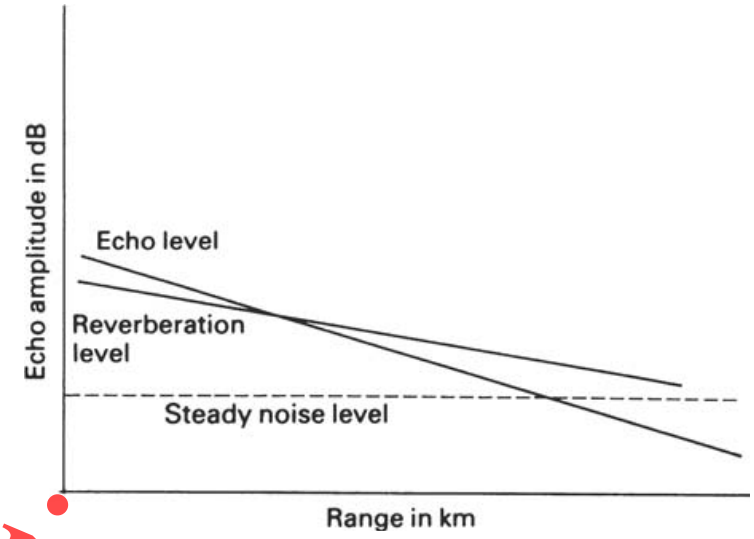

Figure 2.4 Comparison of steady-state noise, reverberation noise and signal amplitude.

2.3 Transducers

A transducer is a converter of energy. RF energy, when applied to a transducer assembly, will cause the unit to oscillate at its natural resonant frequency. If the transmitting face of the unit is placed in contact with, or close to, seawater the oscillations will cause acoustic waves to be transmitted in the water. Any reflected acoustic energy will cause a reciprocal action at the transducer. If the reflected energy comes into contact with the transducer face natural resonant oscillations will again be produced. These oscillations will in turn cause a minute electromotive force (e.m.f.) to be created which is then processed by the receiver to produce the necessary data for display.

Three types of transducer construction are available; electrostrictive, piezoelectric resonator, and magnetostrictive. Both the electrostrictive and the piezoelectric resonator types are constructed from piezoelectric ceramic materials and the two should not be confused.

2.3.1 Electrostrictive transducers

Certain materials, such as Rochelle salt and quartz, exhibit pressure electric effects when they are subjected to mechanical stress. This phenomenon is particularly outstanding in the element lead zirconate titanate, a material widely used for the construction of the sensitive element in modern electrostrictive transducers. Such a material is termed ferro-electric because of its similarity to ferromagnetic materials.

The ceramic material contains random electric domains which when subjected to mechanical stress will line up to produce a potential difference (p.d.) across the two plate ends of the material section. Alternatively, if a voltage is applied across the plate ends of the ceramic crystal section its length will be varied. Figure 2.5 illustrates these phenomena.

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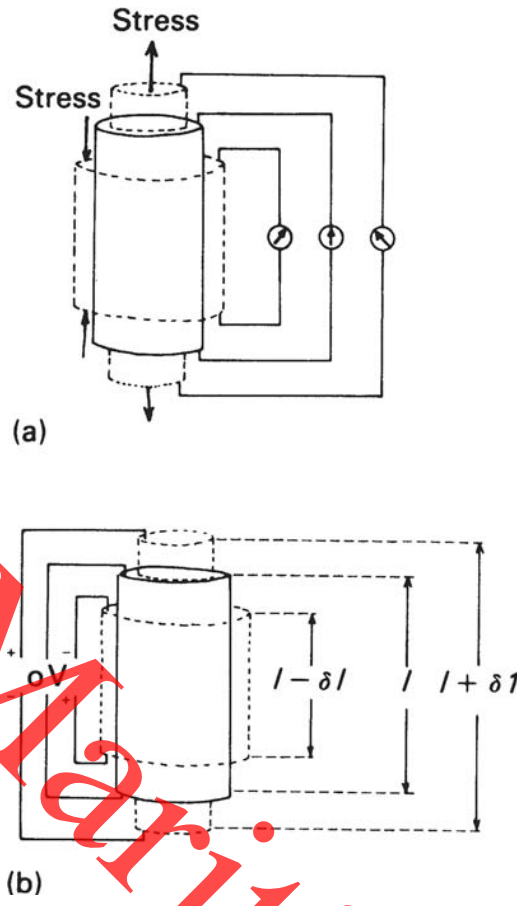

Figure 2.5 (a) An output is produced when a piezoelectric ceramic cylinder is subjected to stress. (b) A change of length occurs if a voltage is applied across the ends of a piezoelectric ceramic cylinder.

The natural resonant frequency of the crystal slice is inversely proportional to its thickness. At high frequencies therefore the crystal slice becomes brittle, making its use in areas subjected to great stress forces impossible. This is a problem if the transducer is to be mounted in the forward section of a large merchant vessel where pressure stress can be intolerable. The fragility of the crystal also imposes limits on the transmitter power that may be applied because mechanical stress is directly related to power. The power restraints thus established make the electrostrictive transducer unsuitable for use in depth sounding apparatus where great depths need to be indicated. In addition, the low transmission frequency requirement of an echo sounder means that such a transducer crystal slice would be excessively thick and require massive transmitter peak power to cause it to oscillate. The crystal slice is stressed by a voltage applied across its ends, thus the thicker the crystal slice, the greater is the power needed to stress it.

The electrostrictive transducer is only fitted on large merchant vessels when the power transmitted is low and the frequency is high, a combination of factors present in Doppler speed logging systems. Such a transducer is manufactured by mounting two crystal slices in a sandwich of two stainless steel cylinders. The whole unit is pre-stressed by inserting a stainless steel bolt through the centre of the active unit as shown in Figure 2.6.

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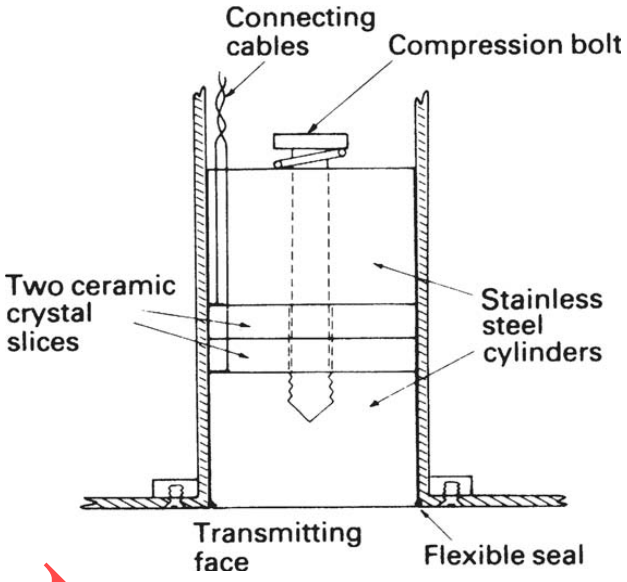

Figure 2.6 Construction details of a ceramic electrostrictive transducer.

If a voltage is applied across the ends of the unit, it will be made to vary in length. The bolt is insulated from the crystal slices by means of a PVC collar and the whole cylindrical section is made waterproof by means of a flexible seal. The bolt tightens against a compression spring permitting the crystal slices to vary in length, under the influence of the RF energy, whilst still remaining mechanically stressed. This method of construction is widely found on the electrostrictive transducers used in the Merchant Navy. For smaller vessels, where the external stresses are not so severe, the simpler piezoelectric resonator is used.

2.3.2 Piezoelectric resonator

This type of transducer makes use of the flexible qualities of a crystal slice. If the ceramic crystal slice is mounted so that it is able to flex at its natural resonant frequency, acoustic oscillations can be produced. The action is again reciprocal. If the ceramic crystal slice is mounted at its corners only, and is caused to flex by an external force, a small p.d. will be developed across the ends of the element.

This phenomenon is widely used in industry for producing such things as electronic cigarette lighters and fundamental crystal oscillator units for digital watches. However, a ceramic crystal slice used in this way is subject to the same mechanical laws as have previously been stated. The higher the frequency of oscillation, the thinner the slice needs to be and the greater the risk of fracture due to external stress or overdriving. For these reasons, piezoelectric resonators are rarely used at sea.

2.3.3 Magnetostrictive transducers

Figure 2.7 shows a bar of ferromagnetic material around which is wound a coil. If the bar is held rigid and a large current is passed through the coil, the resulting magnetic field produced will cause the bar to change in length. This slight change may be an increase or a decrease depending upon the material used for construction. For maximum change of length for a given input signal, annealed nickel has been found to be the optimum material and consequently this is used extensively in the construction of marine transducers.

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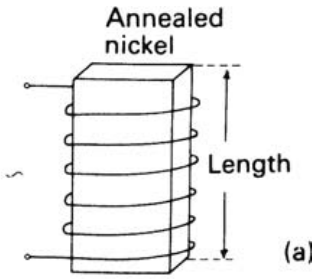

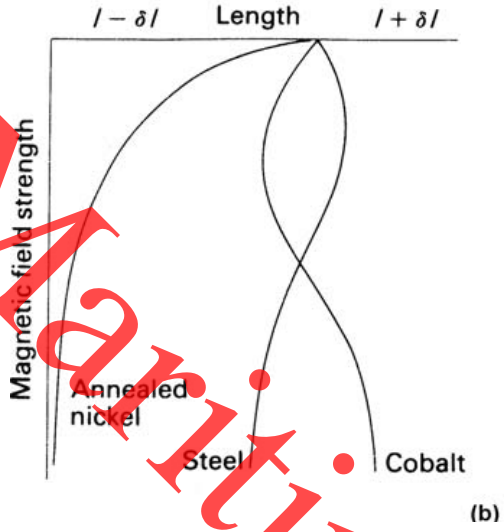

Figure 2.7 (a) A bar of ferromagnetic material around which is wound a coil. (b) Relationship between magnetic field strength and change of length.

As the a.c. through the coil increases to a maximum in one direction, the annealed nickel bar will reach its maximum construction length *(l*+δ*l*). With the a.c. at zero the bar returns to normal (*l*). The current now increases in the opposite direction and the bar once again constricts (*l*–δ*l*). The frequency of resonance is therefore twice that of the applied a.c. This frequency doubling action is counteracted by applying a permanent magnet bias field produced by an in-built permanent magnet.

The phenomenon that causes the bar to change in length under the influence of a magnetic field is called 'magnetostriction', and in common with most mechanical laws possesses the reciprocal quality. When acoustic vibrations cause the bar to constrict, at its natural resonant frequency, an alternating magnetic field is produced around the coil. A minute alternating current is caused to flow in the coil and a small e.m.f. is generated. This is then amplified and processed by the receiver as the returned echo.

To limit the effects of magnetic hysteresis and eddy current losses common in low frequency transformer construction, the annealed nickel bar is made of laminated strips bonded together with an insulating material. Figure 2.8 illustrates the construction of a typical magnetostrictive transducer unit. The transmitting face is at the base of the diagram.

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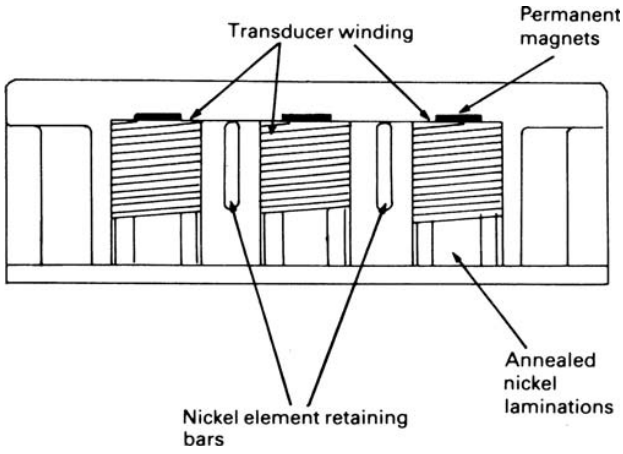

Figure 2.8 Cross-section of a magnetostrictive transducer. (Reproduced courtesy of Marconi Marine.)

Magnetostrictive transducers are extremely robust which makes them ideal for use in large vessels where heavy sea pounding could destroy an unprotected electrostrictive type. They are extensively used with depth sounding apparatus because at the low frequencies used they can be constructed to an acceptable size and will handle the large power requirement of a deep sounding system. However, magnetic losses increase with frequency, and above 100 kHz the efficiency of magnetostrictive transducers falls to below the normal 40%. Above this frequency electrostrictive transducers are normally used.

2.3.4 Transducer siting

The decision of where to mount the transducer must not be made in haste. It is vital that the active face of the transducer is in contact with the water. The unit should also be mounted well away from areas close to turbulence that will cause noise. Areas close to propellers or water outlets must be avoided. Aeration is undoubtedly the biggest problem encountered when transducers are wrongly installed. Air bubbles in the water, for whatever reason, will pass close to the transducer face and act as a reflector of the acoustic energy.

As a vessel cuts through the water, severe turbulence is created. Water containing huge quantities of air bubbles is forced under and along the hull. The bow wave is aerated as it is forced above the surface of the sea, along the hull. The wave falls back into the sea at approximately one-third the distance along the length of the vessel from the bow. A transducer mounted aft of the position where the bow wave re-enters the sea, would suffer badly from the problems of aeration. Mounting the transducer ahead of this point, even in the bulbous bow, would be ideal. It should be remembered, however, that at some stage maintenance may be required and a position in the bulbous bow may be inaccessible. A second source of aeration is that of cavitation. The hull of a vessel is seldom smooth and any indentations or irregularities in it will cause air bubbles to be produced leading to aeration of the transducer face. Hull irregularities are impossible to predict as they are not a feature of the vessel's design.

2.4 Depth sounding principles

In its simplest form, the depth sounder is purely a timing and display system that makes use of a transmitter and a receiver to measure the depth of water beneath a vessel. Acoustic energy is transmitted perpendicularly from the transducer to the seabed. Some of the transmitted energy is reflected and will be received by the transducer as an echo. It has been previously stated that the velocity of sound waves in seawater is accepted to be 1500 ms^{-1}. Knowledge of this fact and the ability

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to measure precisely the time delay between transmission and reception, provides an accurate indication of the water depth.

$$\text{Distance travelled} = \frac{\text{velocity} \times \text{time}}{2}$$

where velocity = 1500 ms^{-1} in salt water; time = time taken for the return journey in seconds; and distance = depth beneath the transducer in metres. Thus if the time taken for the return journey is 1 s, the depth of water beneath the transducer is 750 m. If the time is 0.1 s the depth is 75 m, and so on.

The transmitter and transducer, must be capable of delivering sufficient power and the receiver must possess adequate sensitivity to overcome all of the losses in the transmission medium (seawater and seabed). It is the likely attenuation of the signal, due to the losses described in the first part of this chapter, which determines the specifications of the equipment to be fitted on a merchant vessel.

2.4.1 Continuous wave/pulse system

The transmission of acoustic energy for depth sounding, may take one of two forms.

- A continuous wave system, where the acoustic energy is continuously transmitted from one transducer. The returned echo signal is received by a second transducer and a phase difference between the two is used to calculate the depth.
- The pulse system, in which rapid short, high intensity pulses are transmitted and received by a single transducer. The depth is calculated by measuring the time delay between transmission and reception.

The latter system is preferred in the majority of applications. Both the pulse length (duration) and the pulse repetition frequency (PRF) are important when considering the function of the echo sounding apparatus.

Continuous wave system

This system is rarely used in commercial echo sounding applications. Because it requires independent transmitters and receivers, and two transducer assemblies it is expensive. Also because the transmitter is firing continually, noise is a particular problem. Civilian maritime echo sounders therefore use a pulsed system.

Pulsed system

In this system the transmitter fires for a defined period of time and is then switched off. The pulse travels to the ocean floor and is reflected back to be received by the same transducer which is now switched to a receive mode. The duration of the transmitter pulse and the pulse repetition frequency (PRF) are particularly important parameters in this system

The pulse duration effectively determines the resolution quality of the equipment. This, along with the display method used, enables objects close together in the water, or close to the seabed, to be recorded separately. It is called target or echo discrimination. This factor is particularly important in fish finding apparatus where very short duration pulses (typically 0.25 or 0.5 ms) are used.

Echo discrimination *(D)* is:

$$D = V \times l \text{ (in metres)}$$

where V = the velocity of acoustic waves, and l = pulse length.

For a 0.5 ms pulse length:

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$$D = 1500 \times 0.5 \times 10^{-3} = 0.75m$$

For a 2 ms pulse length:

$$D = 1500 \times 2\ 10^{-3} = 3m$$

Obviously a short pulse length is superior where objects to be displayed are close together in the water. Short pulse lengths tend to be used in fish finding systems.

A short pulse length also improves the quality of the returned echo because reverberation noise will be less. Reverberation noise is directly proportional to the signal strength, therefore reducing the pulse length reduces signal strength which in turn reduces noise. Unfortunately, reducing the signal strength in this way reduces the total energy transmitted, thereby limiting the maximum depth from which satisfactory echoes can be received. Obviously, a compromise has to be made. Most depth sounders are fitted with a means whereby the pulse length can be varied with range. For shallow ranges, and for better definition, a short pulse length is used. On those occasions where great depths are to be recorded a longer pulse is transmitted.

For a given pulse length, the PRF effectively determines the maximum range that can be indicated. It is a measure of the time interval between pulses when transmission has ceased and the receiver is awaiting the returned echo.

The maximum indicated range may be determined by using the following formula:

$$\text{Maximum range indication } (r) = v \cdot t / 2 \text{(in metres)}$$

where v = velocity of sound in seawater (1500 ms^{-1}) and t = time between pulses in seconds. If the PRF is one per second (PRF = 60), the maximum depth recorded is 750 m. If the PRF is two per second (PRF = 120) the maximum depth recorded is 375 m.

The maximum display range should not be confused with the maximum depth. For instance, if the PRF is one per second the maximum display range is 750 m. If the water depth is 850 m, an echo will be returned after a second pulse has been transmitted and the range display has been returned to zero. The indicated depth would now be 100 m. A system of 'phased' ranges, where the display initiation is delayed for a pre-determined period after transmission overcomes the problem of over-range indication.

2.4.2 Transmission beamwidth

Acoustic energy is radiated vertically downwards from the transducer in the form of a beam of energy. As Figure 2.9 shows the main beam is central to the transducer face and shorter sidelobes are also produced. The beamwidth must not be excessively narrow otherwise echoes may be missed, particularly in heavy weather when the vessel is rolling.

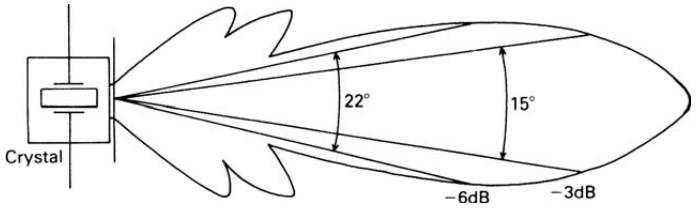

Figure 2.9 Transmission beam showing the sidelobes.

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A low PRF combined with a fast ship speed can in some cases lead to the vessel 'running away' from an echo that could well be missed. In general, beamwidths measured at the half-power points (–3 dB), used for depth sounding apparatus are between 15° and 25°. To obtain this relatively narrow beamwidth, the transducer needs to be constructed with a size equal to many wavelengths of the frequency in use. This fact dictates that the transducer will be physically large for the lower acoustic frequencies used in depth sounding.

In order to reduce the transducer size, and keep a narrow beamwidth, it is possible to increase the transmission frequency. However, the resulting signal attenuation negates this change and in practice a compromise must once again be reached between frequency, transducer size and beamwidth. Figure 2.10 shows typical beamwidths for a low frequency (50 kHz) sounder and that of a frequency four times greater.

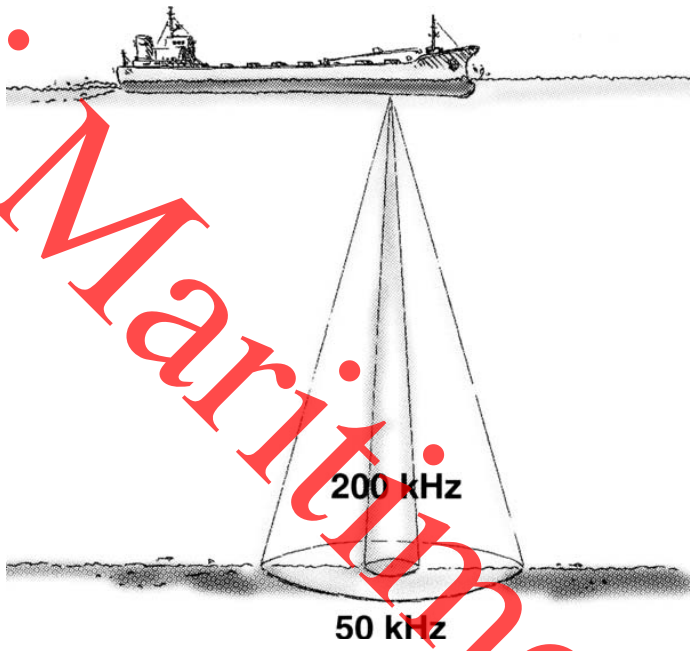

Figure 2.10 Typical beamwidths for echo sounders transmitting low and high frequencies. (Reproduced courtesy Furuno Electric Co. Ltd.)

2.5 A generic echo sounding system

Compared with other systems, echo sounder circuitry is relatively simple. Most manufacturers of deep sounding systems now opt for microprocessor control and digital displays, but it was not always so. Many mariners preferred the paper-recording echo sounder because the display was clear, easy to read and provided a history of soundings.

Marconi Marine's 'Seahorse' echo sounder (Figure 2.11) was typical of the standard paperrecording echo sounder. Built in the period before microprocessor control, it is used here to describe the relatively simply circuitry needed to produce an accurate read-out of depth beneath the keel. From the description it is easy to see that an echo sounding system is simply a timing device.

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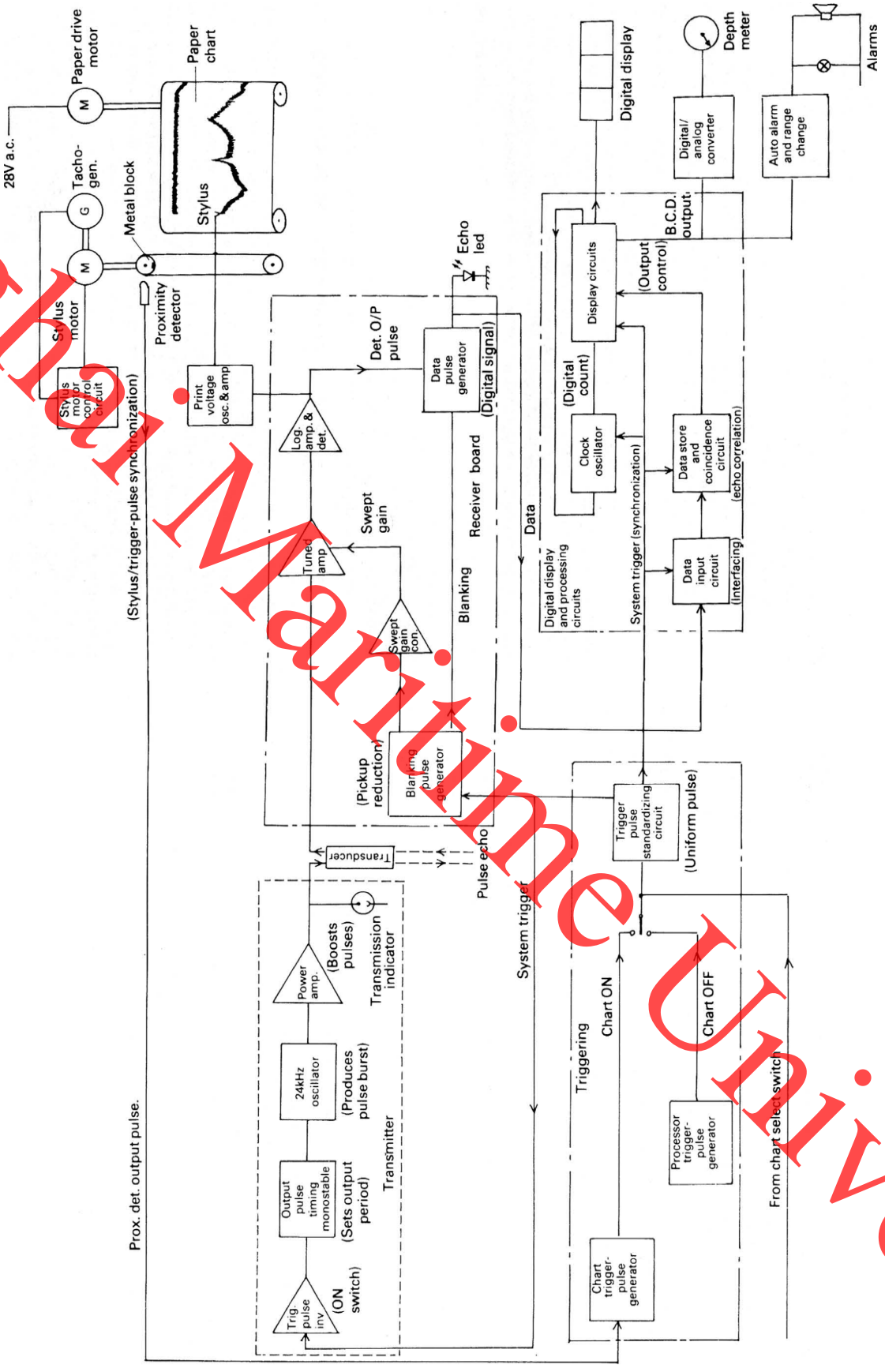

Figure 2.11 A block schematic diagram of the Seahorse echo sounder.
(Reproduced courtesy of Marconi Marine.)

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The system used a transmission frequency of 24 kHz and two ranges, either manually or automatically selected, to allow depths down to 1000 m to be recorded. The shallow range was 100m and operated with a short pulse length of 200 μs, whereas the 1000 m range uses a pulse length of 2 ms. Display accuracy for the chart recorder is typically 0.5% producing indications with an accuracy of ±0.5 m on the 100 m range and ±5 m on the deepest range.

2.5.1 Description

Receiver and chart recorder

When chart recording has been selected, transmission is initiated by a pulse from a proximity detector which triggers the chart pulse generator circuit introducing a slight delay, pre-set on each range, to ensure that transmission occurs at the instant the stylus marks zero on the recording paper. This system trigger pulse or that from the trigger pulse generator circuit when the chart is switched off, has three functions:

- to initiate the pulse timing circuit
- to operate the blanking pulse generator
- to synchronize the digital and processing circuits.

The transmit timing circuit sets the pulse length to trigger the 24 kHz oscillator (transmission frequency). Pulse length is increased, when the deep range is changed, by a range switch (not shown). Power contained in the transmitted signal is produced by the power amplifier stage, the output of which is coupled to the magnetostrictive transducer with the neon indicating transmission.

When the transmitter fires, the receiver input is blanked to prevent the high-energy pulse from causing damage to the input tuned circuits. The blanking pulse generator also initiates the swept gain circuit and inhibits the data pulse generator. During transmission, the swept gain control circuit holds the gain of the input tuned amplifier low. At cessation of transmission, the hold is removed permitting the receiver gain to gradually increase at a rate governed by an inverse fourth power law. This type of inverse gain control is necessary because echoes that are returned soon after transmission ceases are of large amplitude and are likely to overload the receiver.

The echo amplitude gradually decreases as the returned echo delay period increases. Thus the swept gain control circuit causes the average amplitude of the echoes displayed to be the same over the whole period between transmission pulses. However, high intensity echoes returned from large reflective objects will produce a rapid change in signal amplitude and will cause a larger signal to be coupled to the logarithmic amplifier causing a more substantial indication to be made on the paper.

The logarithmic amplifier and detector stages produce a d.c. output, the amplitude of which is logarithmically proportional to the strength of the echo signal.

In the chart recorder display, electrosensitive paper is drawn horizontally beneath a sharp stylus. The paper is tightly drawn over the grounded roller guides by a constant speed paper-drive motor. Paper marking is achieved by applying a high voltage a.c. signal to the stylus which is drawn at 90° to the paper movement, across the surface of the paper on top of the left-hand roller. The paper is marked by burning the surface with a high voltage charge produced through the paper between the stylus and ground. Depending upon the size of the returned echo, the marking voltage is between 440 and 1100 V and is produced from a print voltage oscillator running at 2 kHz. Oscillator amplifier output is a constant amplitude signal, the threshold level of which is raised by the d.c. produced by a detected echo signal. Thus a high-intensity echo signal causes the marking voltage to be raised above the threshold level by a greater amount than would be caused by a detected small echo signal.

For accurate depth marking it is essential that the stylus tracking speed is absolutely precise. The stylus

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is moved along the paper by a belt controlled by the stylus d.c. motor. Speed accuracy is maintained by a complex feedback loop and tacho-generator circuit.

Digital circuits

The digital display section contains the necessary logic to drive the integral three-digit depth display, the alarm circuit, and the remote indicators. Pulse repetition frequency (PRF) of the clock oscillator is pre-set so that the time taken for the three-digit counter to count from 000 to 999 is exactly the same as that taken by the paper stylus to travel from zero to the maximum reading for the range in use. The counter output is therefore directly related to depth.

When the chart recorder is switched off, the digital processing section and the transmitter are triggered from the processor trigger pulse generator circuit. Both the transmit and receive sections work in the same way as previously described. A low logic pulse from the trigger pulse standardizing circuit synchronizes the logic functions. The d.c. output from the receiver detector is coupled via a data pulse generator circuit to the interface system. Unfortunately in any echo sounder it is likely that unwanted echoes will be received due to ship noise, aeration or other factors.

False echoes would be displayed as false depth indications on the chart and would be easily recognized. However, such echoes would produce instantaneous erroneous readings on the digital counter display that would not be so easily recognized. To prevent this happening echoes are stored in a data store on the processing board and only valid echoes will produce a reading on the display.

Valid echoes are those that have indicated the same depth for two consecutive sounding cycles. The data store, therefore, consists of a two-stage counter which holds each echo for one sounding cycle and compares it with the next echo before the depth is displayed on the digital display.

The display circuit consists of three digital counters that are clocked from the clock oscillator circuit. Oscillator clock pulses are initiated by the system trigger at the instant of transmission. The first nine pulses are counted by the lowest order decade counter which registers 1–9 on the display least significant figure (LSF) element. The next clock pulse produces a 0 on the LSF display and clocks the second decade counter by one, producing a 1 in the centre of the display. This action continues, and if no echo is received, the full count of 999 is recorded when an output pulse from the counting circuit is fed back to stop the clock.

Each time transmission takes place the counters are reset to zero before being enabled. This is not evident on the display because the data output from the counters is taken via a latch that has to be enabled before data transfer can take place. Thus the counters are continually changing but the display data will only change when the latches have been enabled (when the depth changes). If an echo is received during the counting process, the output is stopped, and the output latches enabled by a pulse from the data store. The new depth is now displayed on the indicator and the counters are reset at the start of the next transmission pulse.

With any echo sounder, it is necessary that the clock pulse rate be directly related to depth. When the shallow (100 m) range is selected a high frequency is used which is reduced by a factor of 10 when the deep range (1000 m) is selected. Modern echo sounders rely for their operation on the ubiquitous microprocessor and digital circuitry, but the system principles remain the same. It is the display of information that is the outward sign of the advance in technology.

2.6 A digitized echo sounding system

The Furuno Electric Co. Ltd, one of the world's big manufacturers of marine equipment, produces an

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echo sounder, the FE606, in which many of the functions have been digitized. Transmission frequency is either 50 or 200 kHz depending upon navigation requirements. A choice of 50 kHz provides greater depth indication and a wider beamwidth reducing the chance that the vessel may 'run away' from an echo (see Figure 2.10).

The pulse length increases with depth range from 0.4 ms, on the shallow ranges, to 2.0 ms on the maximum range. This enables better target discrimination on the lower ranges and ensures that sufficient pulse power is available on the higher ranges. Pulse repetition rate (sounding rate) is reduced as range increases to ensure adequate time between pulses for echoes to be returned from greater depths.

The system shown in Figure 2.12 is essentially a paper recorder and two LCD displays showing start depth and seabed depth. As before, transmission is initiated at the instant the stylus marks the zero line on the sensitive paper by a trigger sensor coupled to the control integrated circuits. Depending upon the range selected, the pulse length modulates the output from the transmit oscillator, which is power amplified and then coupled via a transmit/receive switch to the transducer. A returned echo is processed in the receiver and applied to the logic circuitry. Here it is processed to determine that it is a valid echo and then it is latched through to a digital-to-analogue converter to produce the analogue voltage to drive the print oscillator. Thus the depth is marked on the sensitive paper at some point determined by the time delay between transmission and reception, and the distance the stylus has travelled over the paper.

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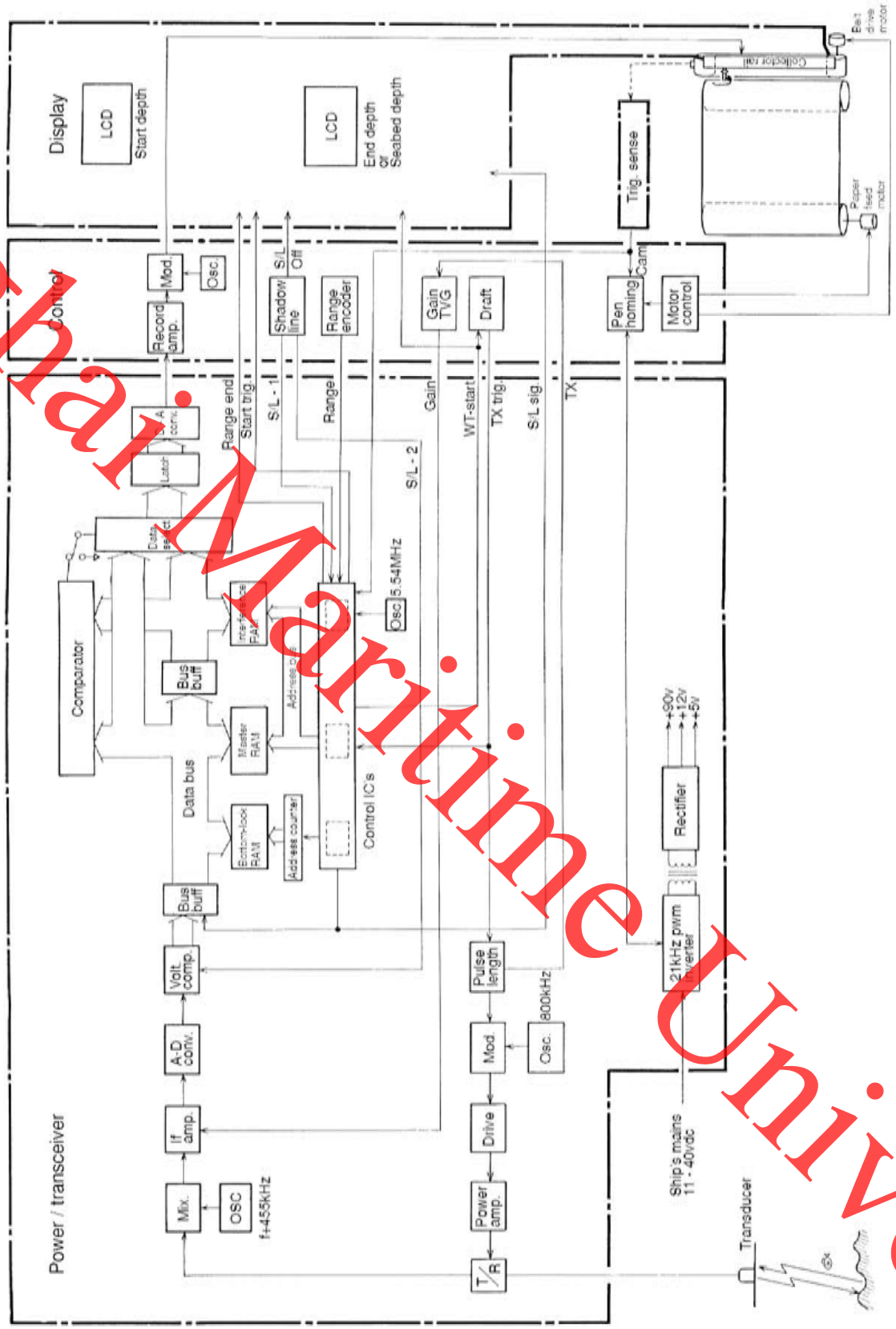

Figure 2.12 Furuno FE-606 echo sounding system.
(Reproduced courtesy of Furuno Electric Co.)

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2.7 A microcomputer echo sounding system

As you would expect, the use of computing technology has eliminated much of the basic circuitry and in most cases the mechanical paper display system of modern echo sounders. Current systems are much more versatile than their predecessors. The use of a computer enables precise control and processing of the echo sounding signal. Circuitry has now reached the point where it is virtually all contained on a few chips. However, the most obvious changes that users will be aware of in modern systems are the display and user interface.

Once again there are many manufacturers and suppliers of echo sounders or, as they are often now called, fish finders. The Furuno navigational echo sounder FE-700 is typical of many. Depending upon requirements the system is able to operate with a 200 kHz transmission frequency giving highresolution shallow depth performance, or 50 kHz for deep-water sounding.

Seabed and echo data is displayed on a 6.5 inch high-brightness TFT colour LCD display which provides the navigator with a history of soundings over a period of 15 min, much as the older paper recording systems did (see Figure 2.13).

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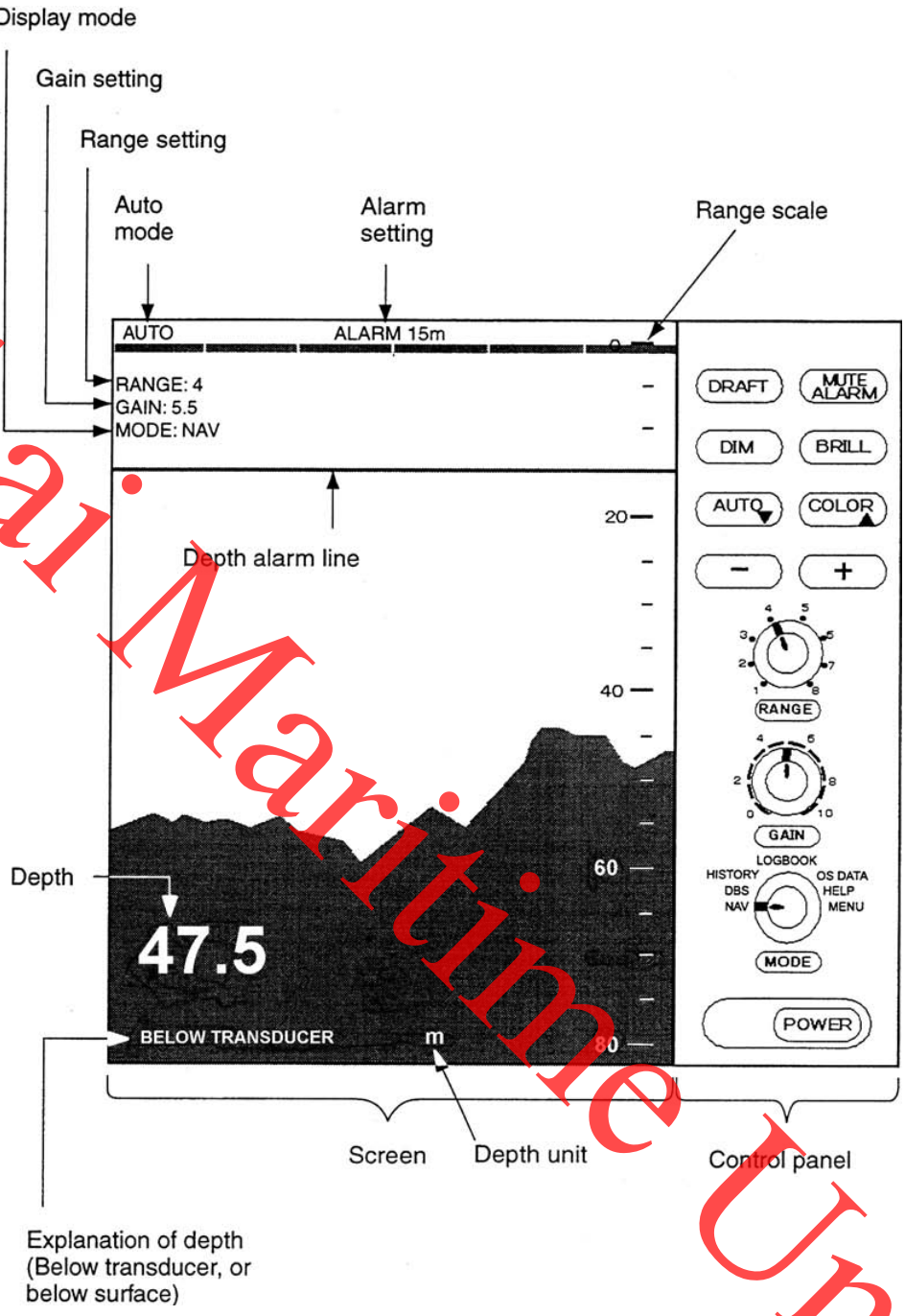

Figure 2.13 Furuno FE-700 LCD TFT data display (Navigation Mode.)
(Reproduced courtesy of Furuno Electric Co.)

Depths, associated time, and position are all stored in 24-h memory and can be played back at any time. This is a useful function if there is any dispute following an accident. The main depth display emulates a cross-sectional profile of the ocean over the past 15 min. At the top of the display in Figure 2.13, the solid zero line marks the ocean surface or transducer level whichever is selected. At 15 m down, a second line marks the depth at which the alarm has been set.

The undulating line showing the ocean floor depth is shown varying over 15 min from 58 to 44 m and the instantaneous depth, also shown as a large numerical display, is 47.5 m. Other operation detail is as shown in the diagram. What is not indicated on the display is the change of pulse length and period as selected by range.

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Table 2.2 Echo sounder range vs pulse length vs PRF

Depth (metres)	*Pulse length (ms)*	*PRF (pulses per minute)*
5, 10 and 20	0.25	750
40	0.38	375
100	1.00	150
200	2.00	75
400 and 800	3.60	42

As shown in Table 2.2, the pulse length is increased with the depth range to effectively allow more power to be contained in the transmitted pulse, whilst the pulse period frequency is reduced to permit longer gaps in the transmission period allowing greater depths to be indicated In addition to the standard navigation mode, Furuno FE-700 users are provided with a number of options adequately demonstrating the capability of a modern echo sounder using a TFT LCD display (see Figure 2.14). All the selected modes display data as a window insert on top of the echo sounder NAV mode display.

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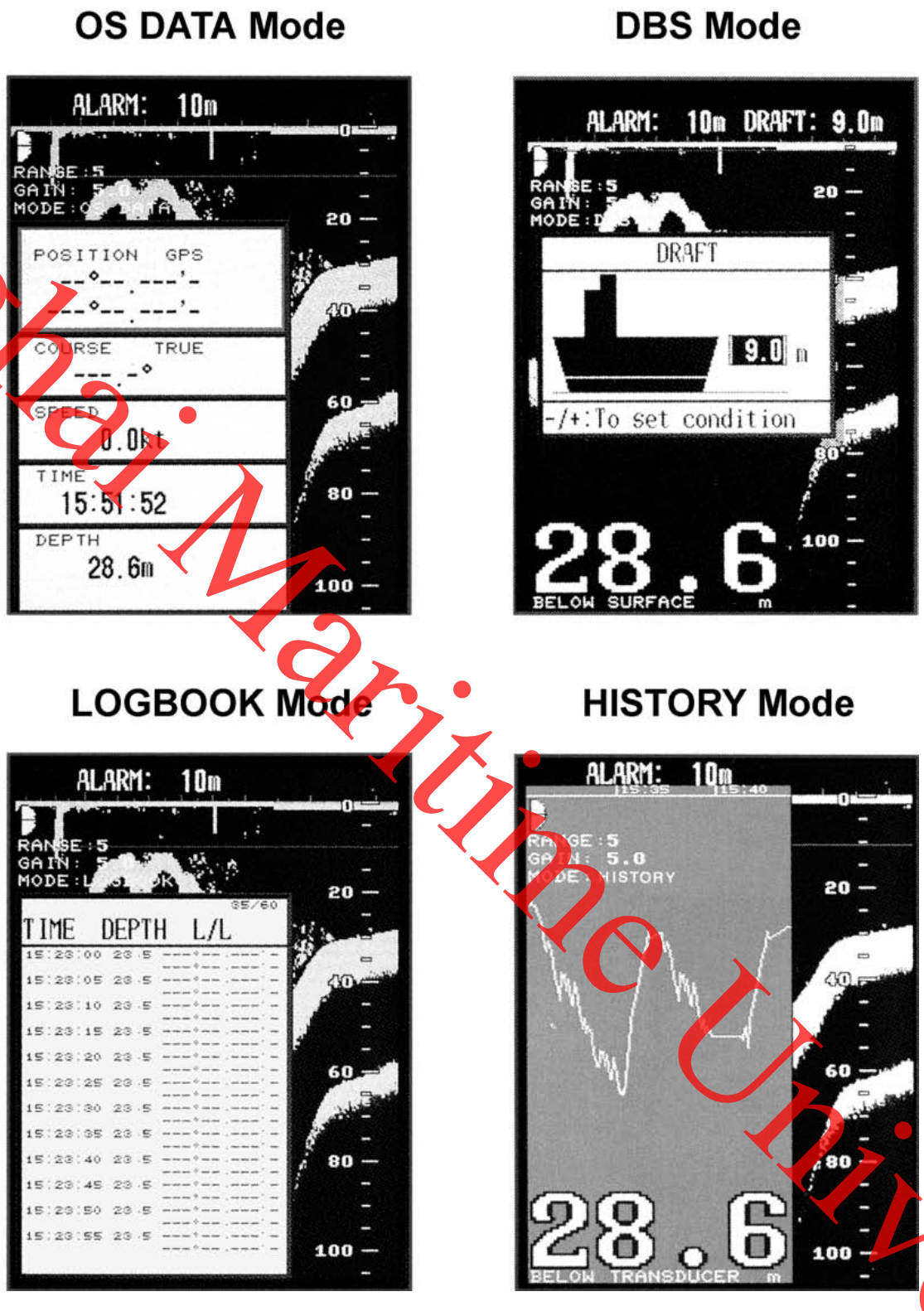

Figure 2.14 Different display modes demonstrating the flexibility of a microcomputer-controlled echo sounder. (Reproduced courtesy of Furuno Electric Co.)

There are four display-mode areas.

- OS DATA mode. Indicates own ship position, GPS derived course, time and a digital display of water depth.
- DBS mode. Provides a draft-adjusted depth mode for referencing with maritime charts.

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- LOGBOOK mode. As the name suggests, provides a facility for manually logging depths over a given period.
- HISTORY mode. Provides a mixture of contour and strata displays. The contour display can be shifted back over the past 24 h whilst the strata display (right-hand side of display) shows sounding data over the last 5 min.

2.8 Glossary

The following lists abbreviations, acronyms and definitions of specific terms used in this chapter.
Aeration Aerated water bubbles clinging to the transducer face cause errors in the system.
Ambient noise Noise that remains constant as range increases.
Beam spreading The transmitted pulse of energy spreads as it travels away from the transducer. The use of a wide beam will cause noise problems in the receiver and a narrow beam may lead to an echo being missed as the vessel steams away from the area.
Chart recorder A sensitive paper recording system which, when the surface is scratched by a stylus, marks the contour of the ocean floor.
Continuous wave system
An echo sounding system that uses two transducers and transmits and receives energy at the same time.
Electrostrictive transducer A transducer design based on piezoelectric technology. It is used when a higher transmission frequency is needed such as in speed logging equipment or fish-finding sounders.
Magnetostrictive transducer A design based on magnetic induction. A large heavy transducer capable of transmitting high power. Used in deep sounding systems.
Pulse duration (length) The period of the transmitted pulse when the transmitter is active.
Pulse repetition frequency (PRF) The number of pulses transmitted per minute by the system. Similar to RADAR
Pulse wave system A system that, like RADAR, transmits pulses of energy from a transducer which is then switched off. The received energy returns to the same transducer.
Reverberation noise Noise that decreases as range increases.
Sonar *So*und *n*avigation *a*nd *r*anging.
Velocity Speed of acoustic waves in seawater; 1505 ms^{-1} or approximated to1500 ms^{-1}.

2.9 Summary

- Sonar stands for *so*und *n*avigation *a*nd *r*anging.
- Sound travels relatively slowly in seawater at 1505 ms^{-1}. This is approximated to 1500 ms^{-1} for convenience.
- The velocity is not a constant, it varies with the salinity of seawater. Ocean salinity is approximately 3.4%.
- Transmitted signal amplitude is attenuated by saltwater and the ocean floor from which it is reflected.
- Noise caused by sea creatures and ocean activity is a major problem affecting sonar equipment.
- The temperature of the seawater affects the velocity of the acoustic wave and consequently affects the accuracy of the displayed data. Temperature sensors are contained in the transducer housing to

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produce corrective data.

- Transducers are effectively the antennas of sonar systems. They transmit and receive the acoustic energy.
- There are two main types of transducer in use; magnetostrictive and electrostrictive. Magnetostrictive transducers are large and heavy and tend to be used only on large vessels. Electrostrictive transducers are lighter and often used in speed logging systems and on smaller craft.
- Low frequencies are often used in deep sounding systems typically in the range 10–100 kHz.
- The depth below the keel is related to the time taken for the acoustic wave to travel to the ocean floor and return. Put simply if the delay is 1 s and the wave travels at 1500 ms^{-1} then the depth is

$0.5 \times 1500 = 750$ m.

- Pulsed systems, like those used in maritime RADAR, are used in an echo sounder. The pulse length or duration determines the resolution of the equipment. A short pulse length will identify objects close together in the water. If all other parameters remain constant, the pulse repetition frequency (PRF), the number of pulses per minute, determines the maximum range that can be indicated.
- The width of the transmitted beam becomes wider as it travels away from the transducer. It should not be excessively narrow or the vessel may 'run away' from, or miss, the returned echo.
- Modern echo sounding equipment is computer controlled and therefore is able to produce a host of other data besides a depth indication.

2.10 Revision questions

1 Why do deep sounding echo sounders operate with a low transmission frequency?
2 For a given ocean depth, how is it possible for returned echoes to vary in strength?
3 If a vessel sails from salt water into fresh water the depth indicated by an echo sounder will be in error. Why is this and what is the magnitude of the error?
4 Noise can degrade an echo sounder display. How does narrowing the transmitted beamwidth reduce system noise and at what cost?
5 Why are electrostrictive transducers used in maritime applications in preference to piezoelectric resonators?
6 Why do marine echo sounding systems use pulsed transmission and not a continuous wave mode of operation?
7 Many echo sounders offer the ability to vary the transmission pulse duration. Why is this?
8 How are the pulse repetition frequency (PRF) and the maximum depth, indicated by an echo sounding system, related?
9 Why is the siting of an echo sounder transducer important?
10 What do you understand by the term target discrimination?
11 What effect may a narrow transmission beamwidth have on returned echoes if a ship is rolling in heavy seas?

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Chapter 3 The Ship's Speed Log

3.1 Introduction

Speed measurement has always been of the utmost importance to the navigator. The accuracy of a dead reckoning position plotted after a long passage without star sights being taken, is dependent upon a sound knowledge of the vessel's heading and speed.

To be of value, the speed of any object must be measured relative to some other point. At sea, speed may be measured relative to either the seabed (ground reference speed) or to the water flowing past the hull (water reference speed). Both of these types of speed measurement are possible and both have their place in modern navigation systems.

This chapter deals with the methods of speed logging that are in general use on board modern vessels. One of these, the pressure tube log, is old but it still gives a satisfactory performance. Another, the electromagnetic log, is often used on smaller vessels and the popular Doppler speed log is to be found everywhere.

3.2 Speed measurement using water pressure

When a tube, with an opening at its base, is vertically submerged in water, a pressure, proportional to the depth to which the tube is submerged, will be developed in the tube. If the tube is held stationary the pressure remains constant and is termed 'static' pressure. If the tube is now moved through the water, whilst keeping the depth to which it is submerged constant, a second pressure called 'dynamic' pressure is developed. The total pressure in the tube, called a Pitot tube, is therefore the sum of both the static and dynamic pressures.

To ensure that the dynamic pressure reading, and thus speed, is accurate, the effect of static pressure must be eliminated. This is achieved by installing a second tube close to the first in such a way that the static pressure produced in it is identical to that created in the Pitot tube but without the pressure increase due to movement through the water (see Figure 3.1).

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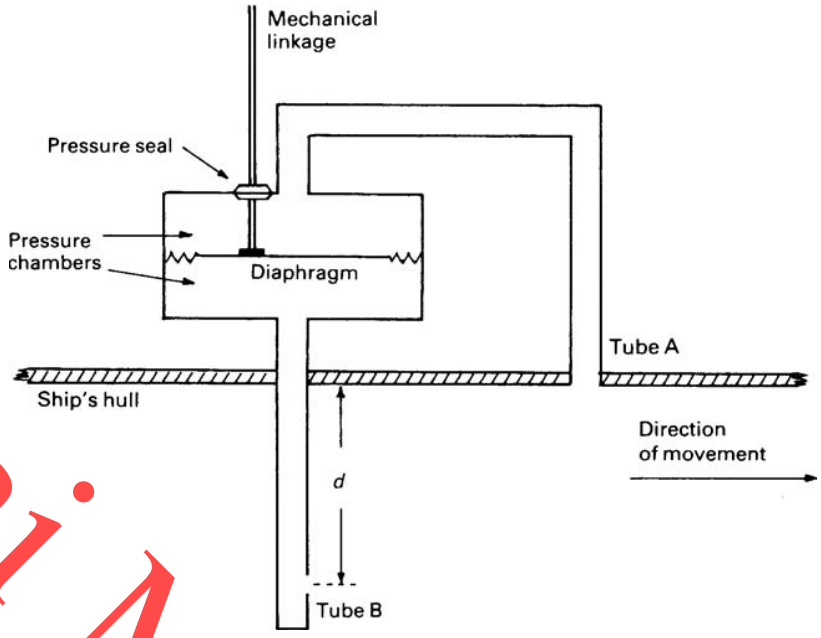

Figure 3.1 The pressure tank and tube intakes of a pressure tube speed logging system.

In a practical installation, tube B, the Pitot tube, extends below the vessel's hull to a depth *d*, whereas tube A, the static pressure intake tube, is flush with the hull. With the vessel stationary, the static pressures from tube A to the top of the diaphragm and tube B to its underside almost cancel. The unequal pressures, which cause a small indication of speed to be displayed when the vessel is stationary, are compensated for in the log electromechanical system and the erroneous indication is cancelled. As the vessel moves through the water, in the direction shown, water is forced into tube B producing a combined pressure in the lower half of the chamber equal to both the static and dynamic pressures. The difference in pressure, between upper and lower chambers, now forces the diaphragm upwards thus operating the mechanical linkage. Obviously the greater the speed of the vessel through the water, the more the diaphragm will move and the greater will be the speed indicated.

Unfortunately, the dynamic pressure developed in tube B, by the relative movement through the water, is proportional to the square of the vessel's speed. Pitot's Law states that this pressure *p* is proportional to the square of the ship's speed *v* multiplied by the coefficient *K*.

$$p = K \times v^2$$

where the constant *K* is derived from the vessel's tonnage, shape of hull, speed of the ship, and the length of the protruding part of the Pitot tube (distance *d*).

As shown in Figure 3.2, the speed indication produced is not linear. It is necessary therefore to eliminate the non-linear characteristics of the system and produce a linear speed indication. This is achieved mechanically, by the use of precisely engineered cones or electronically using CR (capacitive/resistive) time constant circuitry.

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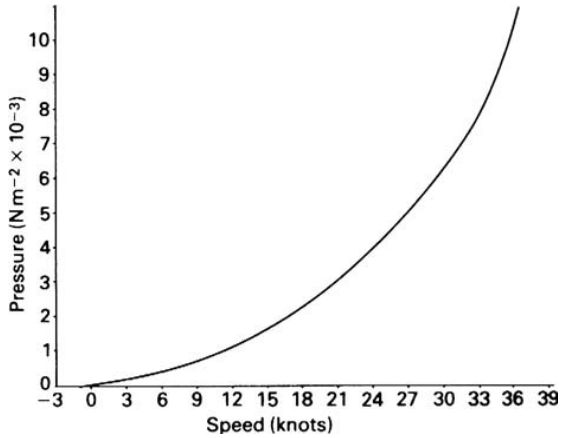

Figure 3.2 Graph indicating the non-linear increase in pressure due to speed.

3.2.1 A pressure tube speed logging system

Figure 3.3 shows a typical installation of the Pitot system on board a vessel with a double bottom. The Pitot tube is encased in a sea-cock arrangement with valve control, to enable the tube to be withdrawn, without shipping water, when the vessel goes alongside. The static pressure opening is controlled by the use of a valve. Both dynamic and static pressures are transferred via air collectors and strainer valves to the pressure chamber. The strainer valves are designed to prevent water oscillations in the interconnecting pipes during operation. Such oscillations would cause the diaphragm to oscillate producing an erratic speed indication.

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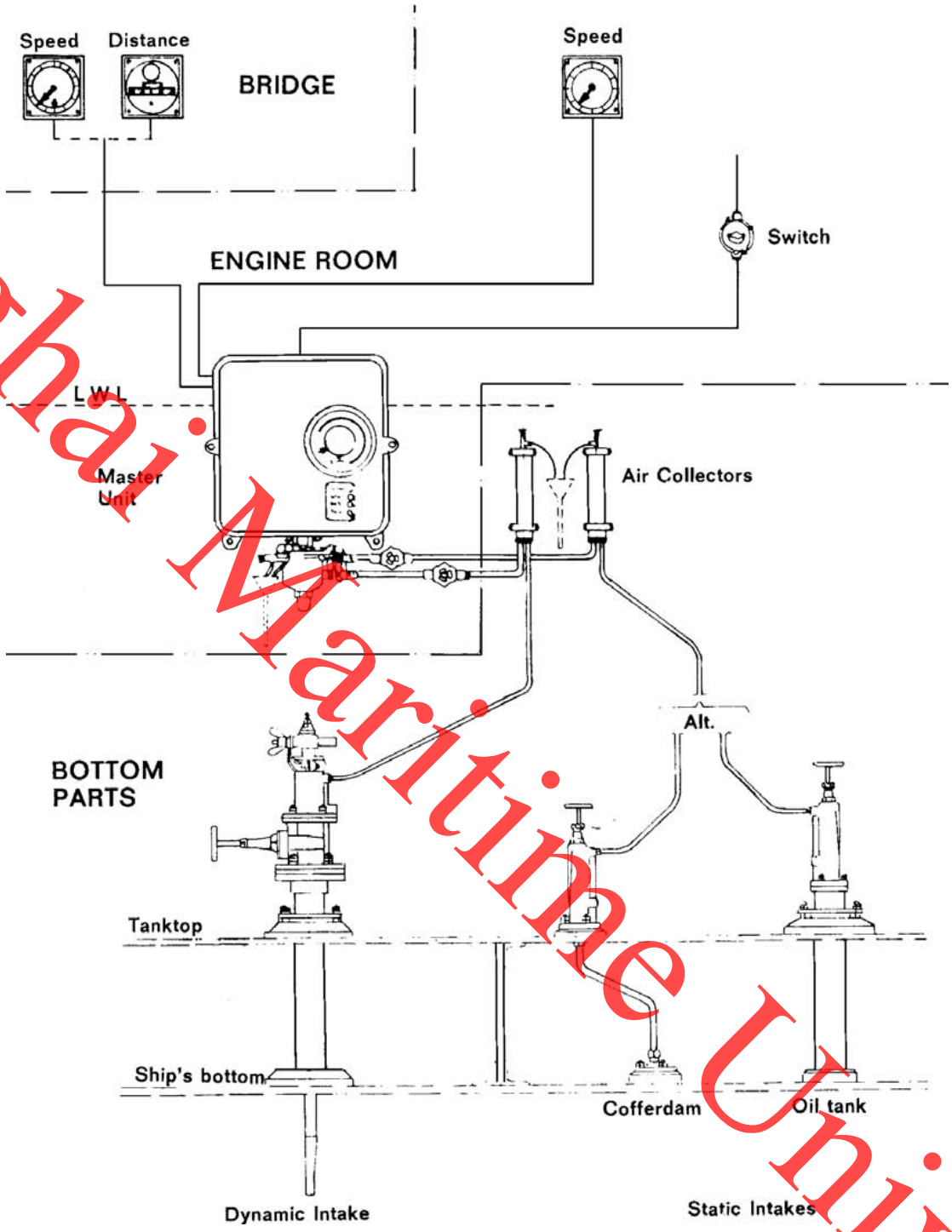

Figure 3.3 A shipboard installation. (Reproduced courtesy of SAL Jungner Marine.)

Figure 3.4 shows the basic speed and distance translating system of a Pitot tube log. The diagram includes two repeating systems for speed and distance data transmission to remote indicators on the ship's bridge. This system was superseded by the SAL24E which replaced some of the mechanical apparatus with electronics. The original log has been included here because it is still in use on many vessels and is a fine example of a pressure type speed logging system.

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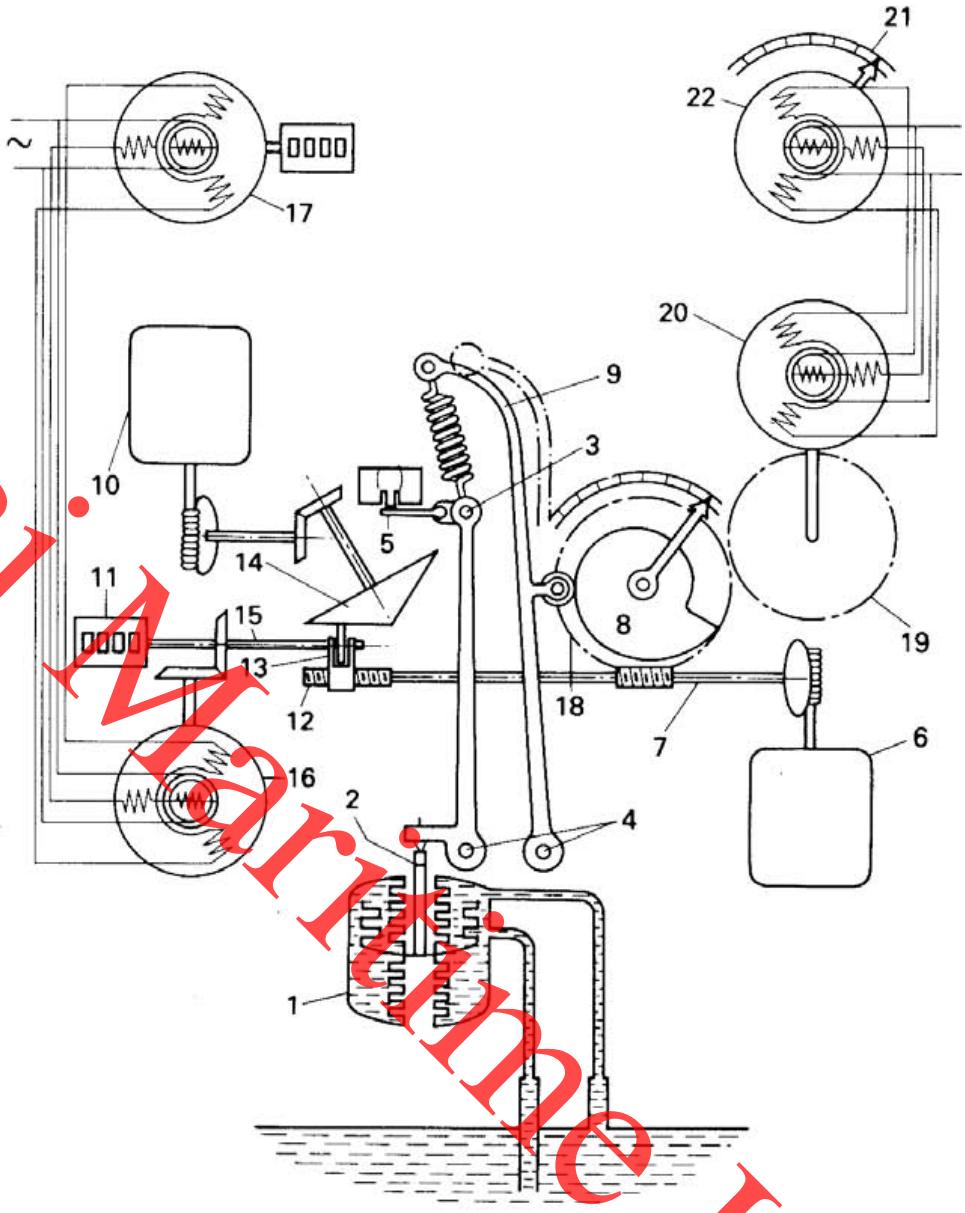

1. pressure chamber
2. pressure rod
3. lever
4. pivot
5. electric start contact
6. reversible motor
7. main shaft
8. spiral cam
9. lever
10. constant speed motor
11. distance counter
12. screw spindle
13. friction wheel
14. distance cone
15. distance shaft
16. servo transmission system
17. servo transmission system
18. gear wheels
19. gear wheels
20. speed servo transmitter
21. remote speed indicator
22. servo receiver

Figure 3.4 The mechanical speed translating system of the SAL 24 pressure tube log. (Reproduced ourtesy of SAL Jungner Marine.)

Description of operation

An increase in the vessel's speed will cause an increase in the dynamic pressure beneath the diaphragm in the pressure chamber (1). This causes the diaphragm to move upwards, pushing the pressure rod (2)

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and moving the lever (3) to the right on pivot (4). The upper end of the lever (3) moves the electric start contact (5) to the right to connect power to a reversible motor (6). The motor now turns causing the main shaft (7) to move a spiral cam (8) clockwise. This action tilts the lever (9), also pivoted on (4), to the left. The deflection stretches the main spring, producing a downward pressure on the diaphragm, via lever (3), causing it to cease rising at an intermediate position. This is achieved when equilibrium has been established between the dynamic pressure, acting on the lower side of the diaphragm, and the counter pressure from the spring on the upper side. At this point the motor (6) stops and thus holds the spiral cam (8) in a fixed position indicating speed.

This method of pressure compensation provides accurate indications of speed independent of alterations of the diaphragm caused by ageing. The shape of the spiral cam (8) has been carefully calculated to produce a linear indication of speed from the non-linear characteristics of the system. Also attached to the spiral cam is a second gearing mechanism (19) that transfers the movement of the speed indicator to the three-phase speed transmission system (20). An identical servo-receiver (22) is fitted in the remote speed repeater unit fitted on the ship's bridge and thus remote speed indication has been achieved.

Distance recording is achieved by using a constant speed motor (10) which drives the distance counter (11), via friction gearing. The constant speed motor has been used in order that a distance indication may be produced that is independent of the non-linear characteristic of the system. The motor is started by contact (5) as previously described. The main shaft (7), whose angle of rotation is directly proportional to the speed of the ship, is fitted with a screw spindle (12). The rotation of the shaft causes a lateral displacement of the friction wheel (13). At zero speed, the friction wheel rests against the apex of the distance cone (14), whilst at maximum speed the wheel has been displaced along the cone to the rim. The distance indicator (11) is driven from the constant speed motor (10) via the cone. The nearer to the rim of the cone the friction wheel rides, the greater will be the distance indication. Revolutions of the distance shaft (15) are transmitted to the remote distance indicator via the servo transmission system (16 and 17).

Operation of the SAL 24E

The SAL 24E utilizes the same system of tubes, pressure tank and diaphragm to convert pressure variations due to speed, to electrical pulses suitable to drive the electronic circuits that replace much of the mechanical arrangement of the SAL 24 log. The distance integration mechanism with servo, cone and counter has been fully replaced with electronic circuitry.

As previously described, when the vessel moves forwards, the dynamic pressure acting on the underside of the diaphragm causes it to move upwards forcing the pushrod upwards. As shown in Figure 3.5, this causes the pushrod arm assembly to move to the right on the pivot, increasing the tension on the spring assembly and producing an output from the differential transformer. This output is applied to the USER board, shown in Figure 3.6, where it is processed to provide the drive for the speed servo-control winding via a ± 24 V switching amplifier. The servo now turns and rotates the cam assembly via gearing and the drive shaft. An increase in speed is now shown on the speed pointer. As the cam rotates it forces the balance arm to the left and tightens the spring until the pushrod arm and the diaphragm bellows are balanced. The cam is carefully designed so that the spring force is proportional to the square of the rotation angle and thus the non-linearity of the pressure system is counteracted. The speed potentiometer turns together with the speed pointer to provide an input to the UDIS board. This input produces a variety of outputs enabling the system to be interfaced with other electronic equipment.

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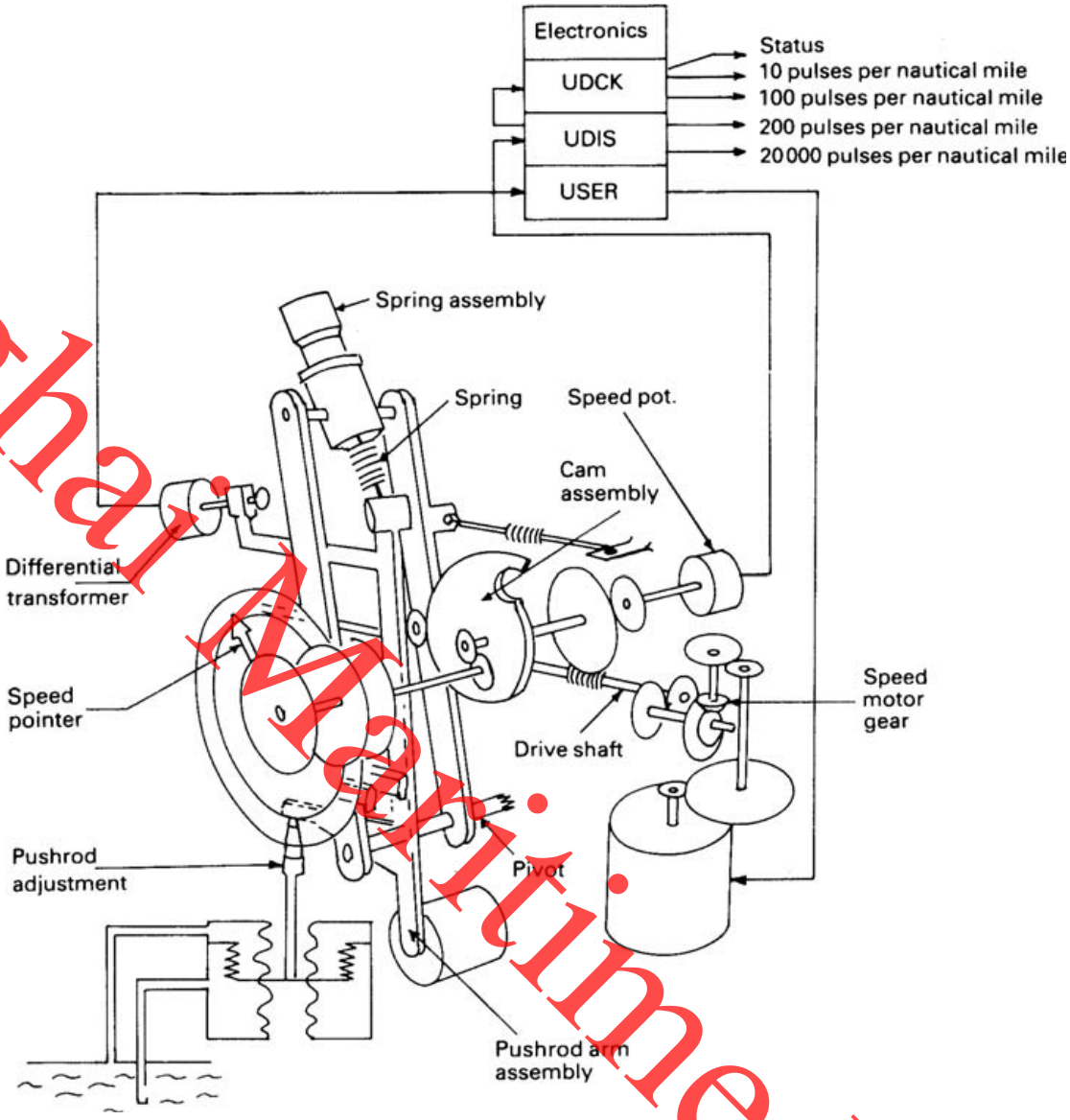

Figure 3.5 Pressure/mechanical assembly of the SAL 24E electronic pressure speed log. (Reproduced courtesy of SAL Jungner Marine.)

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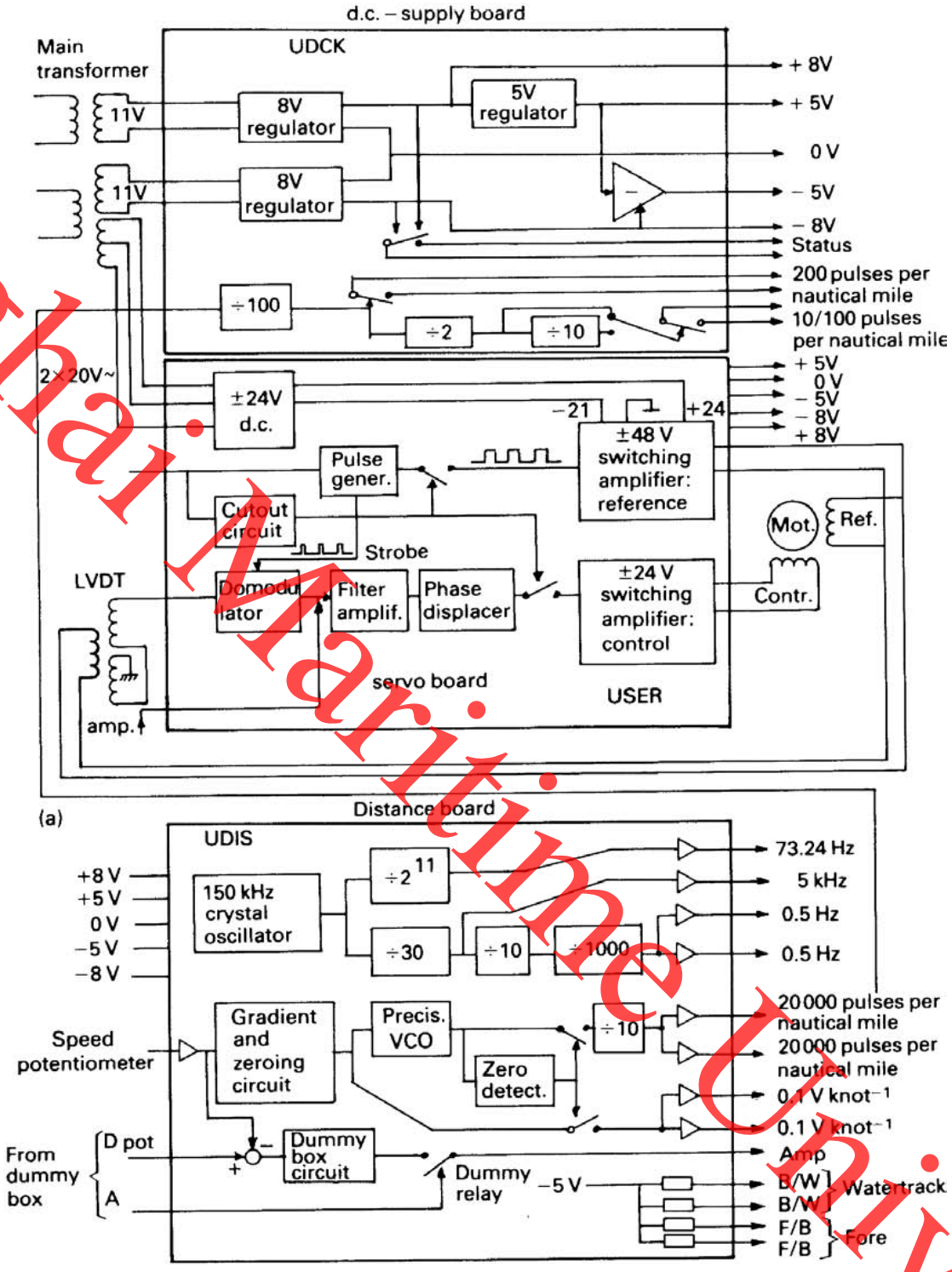

Figure 3.6 The electronics unit. (Reproduced courtesy of SAL Jungner Marine.)

The accuracy of the Pitot type speed log when correctly installed and calibrated is typically better than 0.75% of the range in use.

3.3 Speed measurement using electromagnetic induction

Electromagnetic speed logs continue to be popular for measuring the movement of a vessel through water. This type of log uses Michael Faraday's well-documented principle of measuring the flow of a

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fluid past a sensor by means of electromagnetic induction.

The operation relies upon the principle that any conductor which is moved across a magnetic field will have induced into it a small electromotive force (e.m.f.). Alternatively, the e.m.f. will also be induced if the conductor remains stationary and the magnetic field is moved with respect to it.

Assuming that the magnetic field remains constant, the amplitude of the induced e.m.f. will be directly proportional to the speed of movement.

In a practical installation, a constant e.m.f. is developed in a conductor (seawater flowing past the sensor) and a minute current, proportional to the relative velocity, is induced in a collector. The magnetic field created in the seawater is produced by a solenoid which may extend into the water or be fitted flush with the hull. As the vessel moves, the seawater (the conductor) flowing through the magnetic field has a small e.m.f. induced into it. This minute e.m.f., the amplitude of which is dependent upon the rate of cutting the magnetic lines of force, is detected by two small electrodes set into the outer casing of the sensor.

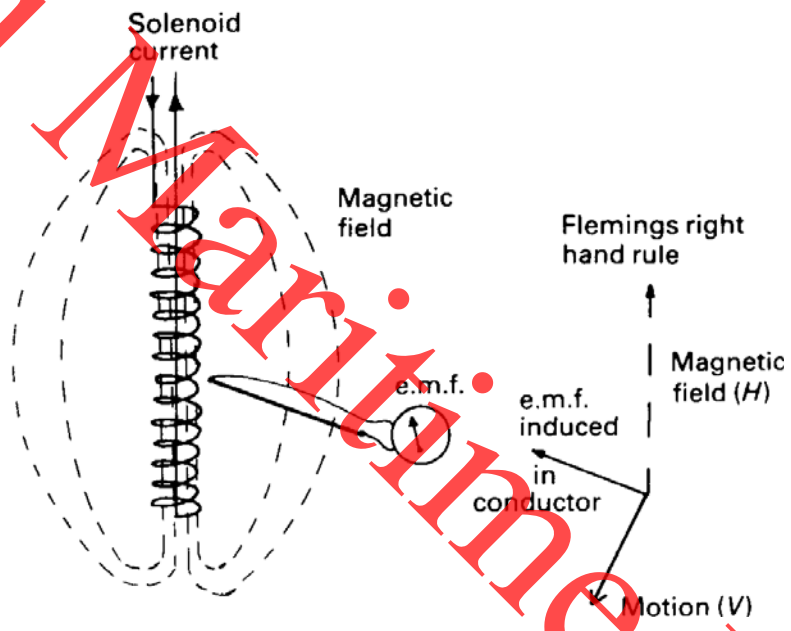

Figure 3.7 Effect of moving a conductor through a magnetic field.

Figure 3.7 shows a solenoid generating a magnetic field and a conductor connected in the form of a loop able to move at right angles to the field. If the conductor is moved in the direction shown, a tiny current will be induced in the wire and a small e.m.f. is produced across it. In the case of an electromagnetic speed log, the conductor is seawater passing through the magnetic field. Fleming's right-hand rule shows that the generated e.m.f. is at right angles to the magnetic field (*H*). Induced current flowing in the conductor produces an indication of the e.m.f. on the meter. If we assume that the energizing current for the solenoid is d.c. the induced e.m.f. is βlv, where _ = the induced magnetic field, l = the length of the conductor, and v = the velocity of the conductor. β is approximately equal to H, the magnetic field strength. Therefore, e.m.f. = Hlv assuming no circuit losses.

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To reduce the effects of electrolysis and make amplification of the induced e.m.f. simpler, a.c. is used to generate the magnetic field. The magnetic field strength H now becomes $H\sin\omega t$ and the induced e.m.f. is: $Hmlv\sin\_t$. If the strength of the magnetic field and the length of the conductor both remain constant then, e.m.f. ≅velocity.

Figure 3.8 illustrates that the changes of e.m.f., brought about by changes in velocity, produce a linear graph and thus a linear indication of the vessel's speed. The e.m.f. thus produced is very small but, if required, may be made larger by increasing the energizing current, or the number of turns of wire on the solenoid.

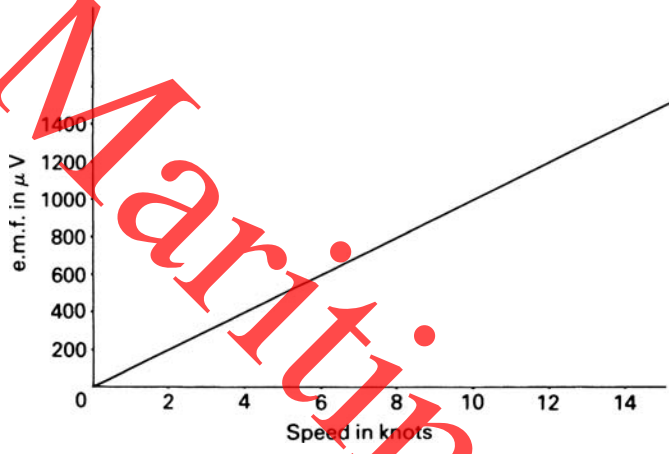

Figure 3.8 Relationship between the vessel's speed and the output from the sensors.

The following points should be noted.

- The a.c. supply to the solenoid produces inductive pick-up between the coil and the wires that carry the signal. This in turn produces a 'zero' error that must be compensated for by 'backing off' the zero setting of the indicator on calibration.
- The induced e.m.f. is very small (for reasonable amplitudes of energizing current), typically l00 μV per knot.
- The induced e.m.f. and hence the speed indication will vary with the conductivity of the water.
- The device measures the speed of the water flowing past the hull of the ship. This flow can vary due to the non-linearity of a hull design.
- Ocean currents may introduce errors.
- Pitching and rolling will affect the relationship between the water speed and the hull. Error due to this effect may be compensated for by reducing the sensitivity of the receiver. This is achieved using a CR timing circuit with a long time constant to damp out the oscillatory effect.
- Accuracy is typically 0.1% of the range in use, in a fore and aft direction, and approximately 2% thwartships.

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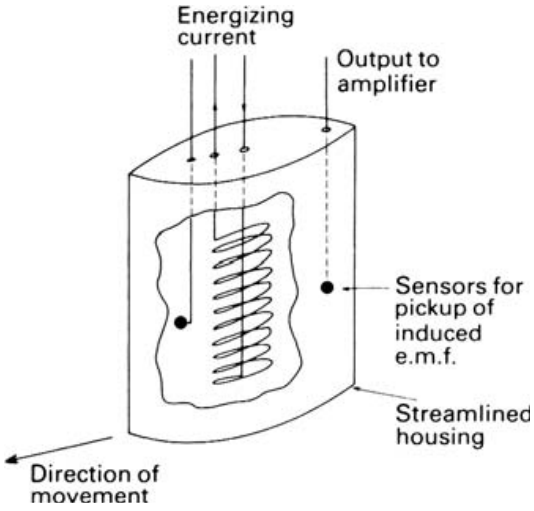

Figure 3.9 Constructional details of an electromagnetic log sensor.

Figure 3.9 shows a typical sensor cutaway revealing the solenoid and the pick-up electrodes. A speed translating system is illustrated in Figure 3.10.

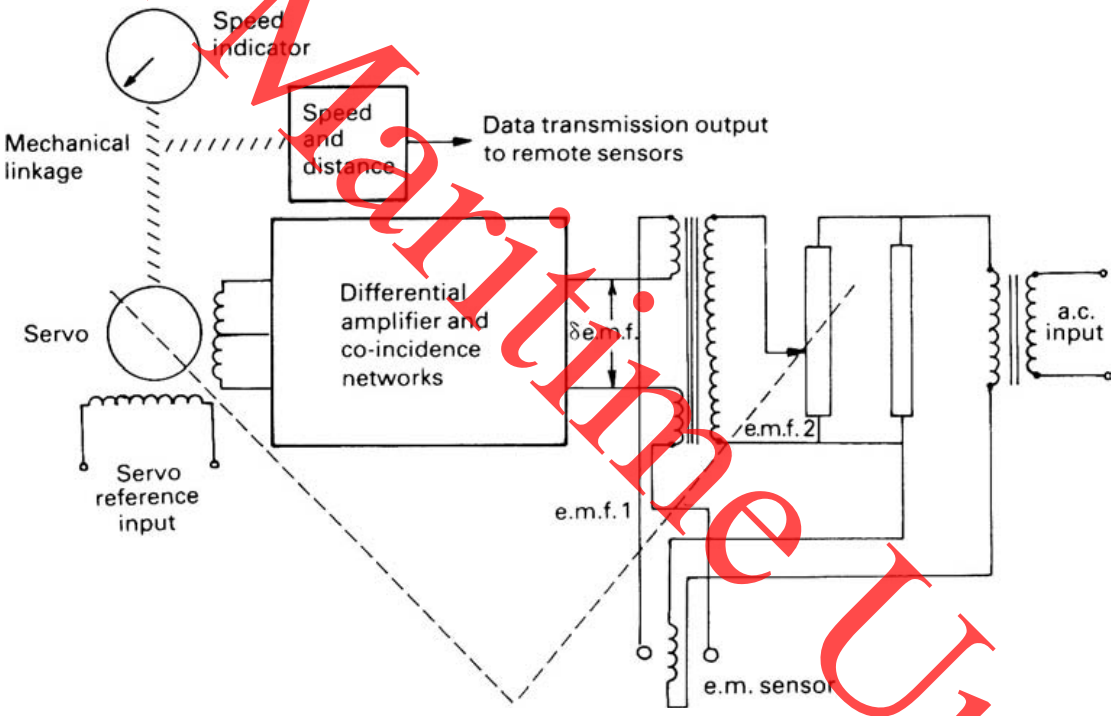

Figure 3.10 An e.m. speed log translating system.

Description of the speed translating system

The small signal speed voltage from the sensor, e.m.f.1, is applied to a differential transformer where it is compared to a reference voltage, e.m.f.2, produced from a potentiometer across the input a.c. supply. The potential difference produced across the reference resistor provides the energizing current for the solenoid in the sensor.

If the signal voltage e.m.f.1. differs from the reference voltage e.m.f.2. an error signal voltage δ e.m.f.

is produced. This error voltage is applied to the speed signal amplifier where it is amplified to produce sufficient power to drive the servo motor. The servo will in turn produce a speed reading, via a

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mechanical linkage, on the indicator. Also coupled to the servo shaft is the slider of the speed potentiometer that turns in the direction to reduce the error voltage _ e.m.f. When this error voltage drops to zero the servo ceases to turn. The speed indicator is stationary until the next error voltage δ e.m.f. is produced. Each time an error voltage is created the servo turns to cancel the error and thus balances the system.

3.3.1 A practical electromagnetic speed logging system

The potential developed across the transducer electrodes is proportional to magnetic field strength (and consequently the energizing current) and the flow velocity in the volume of water influenced by the field. The magnetic field strength is in no way stabilized against any changes in the ship's main voltage, temperature, etc, but by effectively comparing the energizing current with the voltage at the electrodes, their ratio provides a measure of the ship's speed.

The input transformer T1 (shown in Figure 3.11) possesses a very high inductance and a step-down ratio of 5:1. This results in an input impedance, as seen by the pick-up electrodes, approaching 20 MΩ which when compared with the impedance presented by salt water can be considered an open circuit. Hence changes in salinity have no effect on the measured voltage and the resulting speed indication. A switched resistor chain (R1/R5) sets the gain of the overall amplifier in conjunction with resistor chain (R6/R10) which controls the amplitude of the feedback signal.

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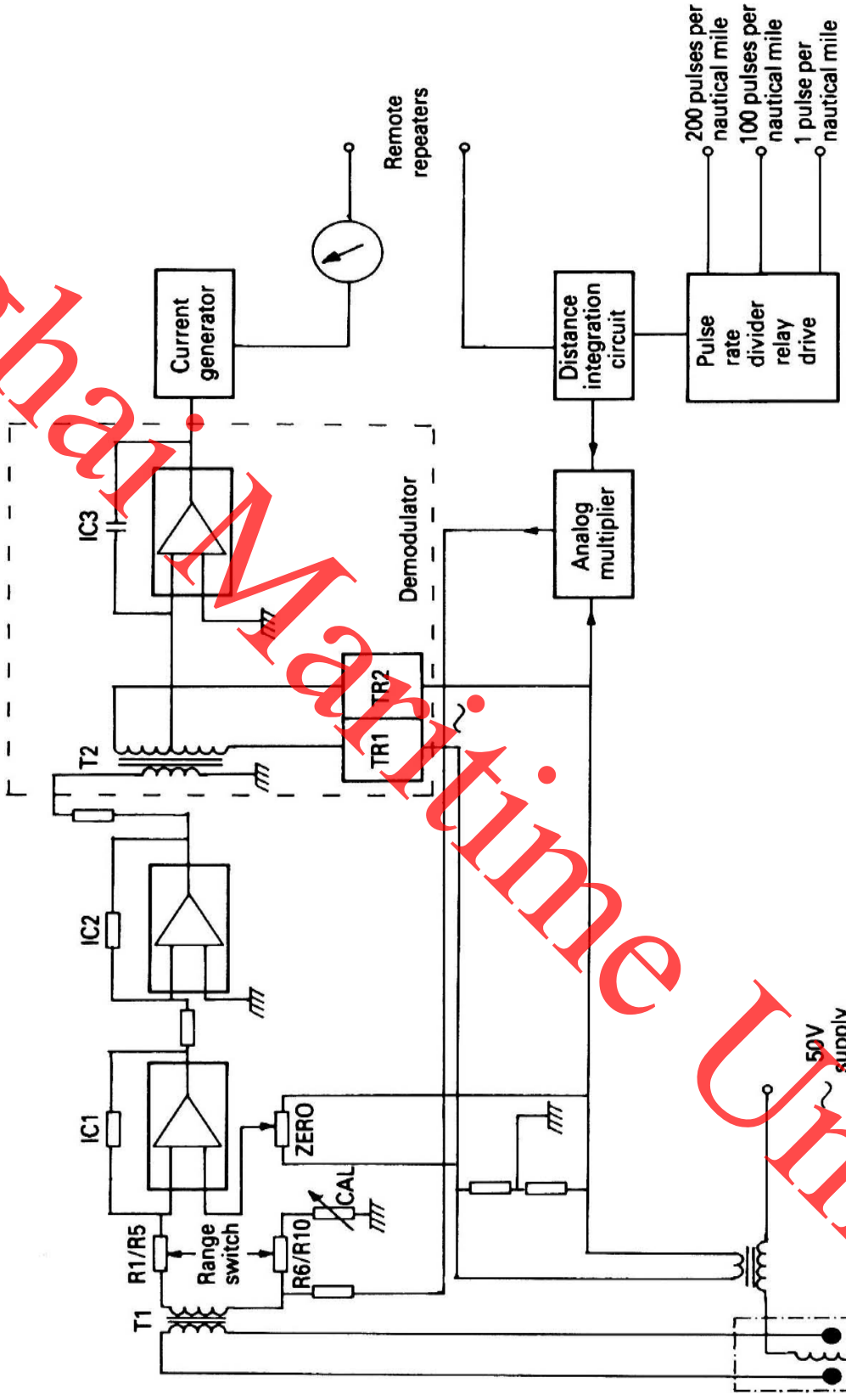

Figure 3.11 Simplified diagram of an e.m. log.

(Reproduced courtesy of Thomas Walker and Son Ltd.)

The output of IC1 is coupled, via IC2, which because of capacitive feedback (not shown), ensures that the circuit has a zero phase shift from T1 through T2, to the demodulator. Demodulation is carried out

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by TR1/TR2 that are switched in turn from an a.c. reference voltage derived from a toroidal transformer monitoring the energizing current of the transducer. By driving TR1/TR2 synchronously, the phase relationship of the voltage detected by the electrodes determines the polarity of the demodulated signal. 0° and 180° phasing produce a positive or negative component; 90° and 270° produce no output and hence a complete rejection of such phase-quadrature signals. The demodulated signal is applied to the Miller Integrator IC3 which in turn drives the current generator. Speed repeaters are current-driven from this source.

Operation of the loop

With no vessel movement, there will be a zero signal at the input to IC1 and consequently there will be no signal at the multiplier chip input. No feedback signal is developed at the input to IC1. As the vessel moves ahead, the small signal applied to IC1 is processed in the electronic unit to produce a current flow through the speed repeaters and the multiplier. There now exists an output from the multiplier, proportional to the speed repeater current and the reference voltage produced by the toroidal transformer monitoring the transducer energizing current. The a.c. from the multiplier is fed back to IC1 in series with, and 180° out of phase with, the small signal secondary of T1. This a.c. signal rises slowly and eventually, with the time constant of the demodulator, is equal to the signal p.d. developed across T1. At this time the resultant signal applied to IC1 falls to zero and therefore the demodulator output remains at a constant figure. Any further change in speed results in an imbalance in the secondary of T1 producing a resultant a.c. signal to IC1. As a result, the demodulator output increases or decreases (faster or slower ship's speed) until the balance condition is restored. The speed repeaters will indicate the appropriate change of speed.

Distance integration

The speed current is passed through a resistive network on the distance integration board, in order that a proportional voltage may be produced for integration. The output of this board is a pulse train, the rate of which is proportional to the indicated speed. The 10 ms pulses are coupled to the relay drive board which holds the necessary logic to give the following outputs: 200 pulses per nautical mile, 100 pulses per nautical mile, and 1 pulse per nautical mile.

3.4 Speed measurement using acoustic correlation techniques

Unlike the previously described speed log, which measure the vessel's speed with respect to water only, the SAL-ICCOR log measures the speed with respect to the seabed or to a suspended water mass. The log derives the vessel's speed by the use of signal acoustic correlation. Simply, this is a way of combining the properties of sonic waves in seawater with a correlation technique. Speed measurement is achieved by bottom-tracking to a maximum depth of 200 m. If the bottom echo becomes weak or the depth exceeds 200 m, the system automatically switches to water-mass tracking and will record the vessel's speed with respect to a water mass approximately 12 m below the keel.

The transducer transmits pulses of energy at a frequency of 150 kHz from two active piezoceramic elements that are arranged in the fore and aft line of the vessel (see Figure 3.12). Each element transmits in a wide lobe perpendicular to the seabed. As with an echo sounder, the transducer elements are switched to the receive mode after transmission has taken place.

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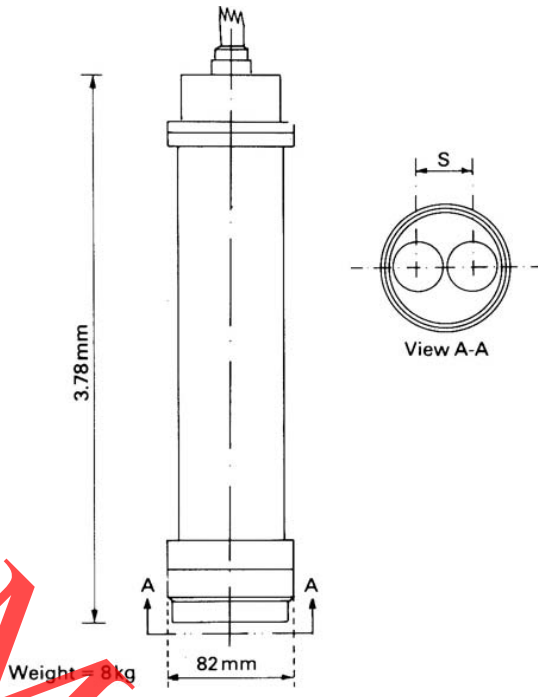

Figure 3.12 Piezoelectric ceramic transducer for the SAL acoustic correlation speed log.

The seabed, or water mass, reflected signals possess a time delay (T) dependent upon the contour of the seabed, as shown in Figure 3.13. Thus the received echo is, uniquely, a function of the instantaneous position of each sensor element plus the ship's speed. The echo signal, therefore, in one channel will be identical to that in the other channel, but will possess a time delay as shown.

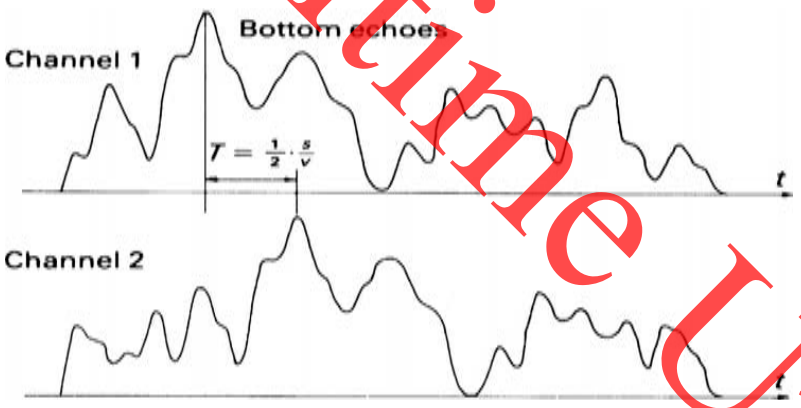

Figure 3.13 Illustration of the time delay (T) between each channel echo signal.

The time delay (T), in seconds, can be presented as:

$$T = 0.5 \times s\, v$$

where s = the distance between the receiving elements and v = the ship's velocity.

In the SAL-ACCOR log (see Figure 3.14), the speed is accurately estimated by a correlation technique. The distance between the transducer elements (s) is precisely fixed, therefore when the time (T) has been determined, the speed of the vessel (v) can be accurately calculated.

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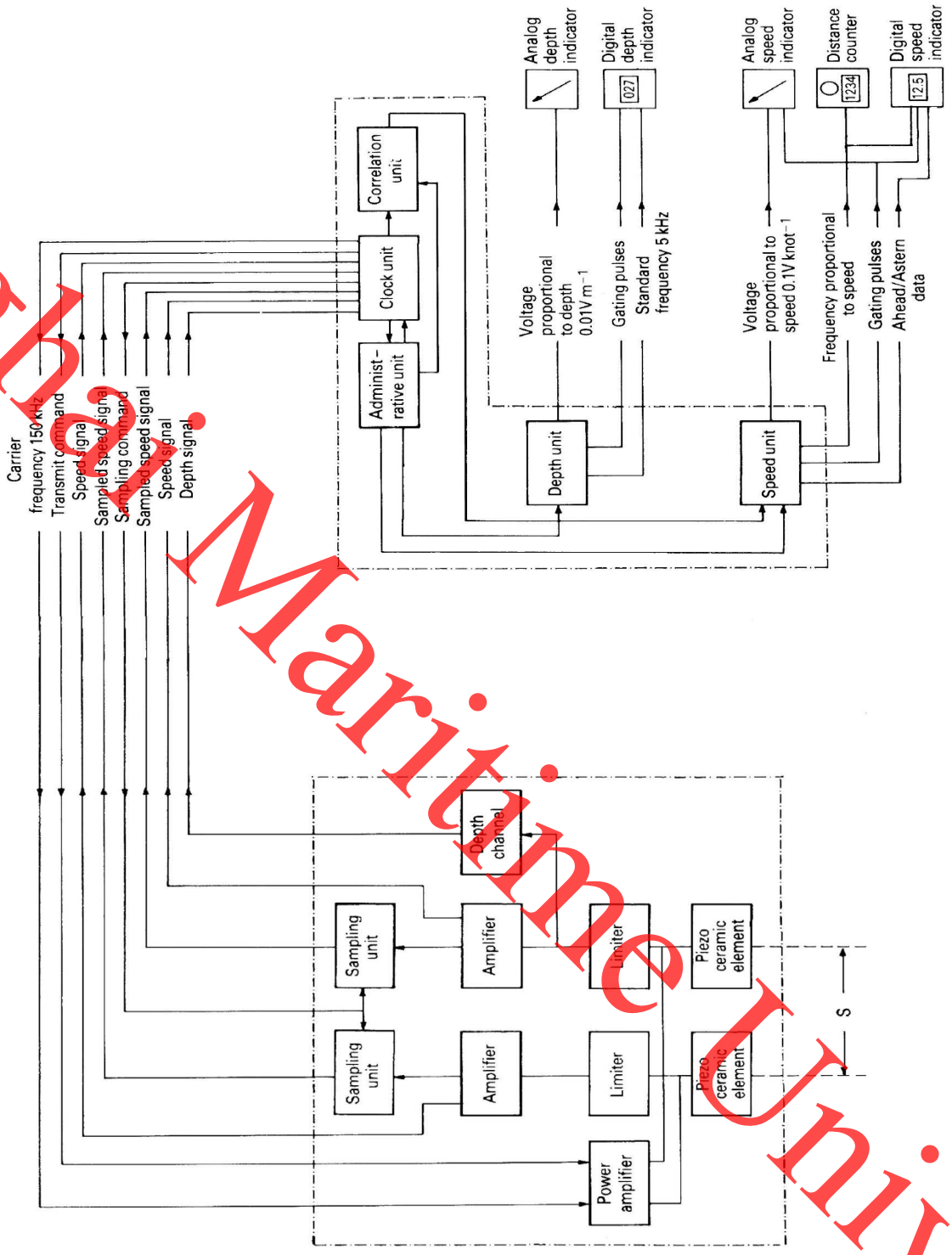

Figure 3.14 System diagram of the SAL-ACCOR acoustic correlation speed log.
(Reproduced courtesy of SAL Junger Marine.)

It should be noted that the calculated time delay (T) is that between the two transducer echoes and not that between transmission and reception. Temperature and salinity, the variables of sound velocity in seawater, will not affect the calculation. Each variable has the same influence on each received echo channel. Consequently the variables will cancel.

It is also possible to use the time delay (T) between transmission and reception to calculate depth.

In this case the depth (d),in metres, is:

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$$d = T \times C / 2$$

where C = the velocity of sonic energy in seawater (1500 ms^{-1}).

Dimensions of the transducer active elements are kept to a minimum by the use of a high frequency and a wide lobe angle. A wide lobe angle (beamwidth) is used because echo target discrimination is not important in the speed log operation and has the advantage that the vessel is unlikely to 'run away' from the returned echo.

3.4.1 System description

Initiating the sequence, the power amplifier produces the transmitted power, at the carrier frequency of 150 kHz, under the command of a pulse chain from the clock unit. Returned echoes are received by two independent identical channels and are pre-amplified before being applied to sampling units. Each sampling unit effectively simplifies the echo signal to enable interconnection to be made between transducer and main unit without the risk of signal deterioration. As with other functions, sampling is commanded by a clock unit, which also provides a highly stable 150 kHz for the carrier frequency. This frequency is also used as a standard frequency for the other functions on the electronics board, where it is divided to produce the 5 kHz needed to operate some of the speed indicators.

As the name suggests, the administration block controls most of the electronic functions. This block initiates the transmit/receive cycle, determines whether the system selects B-track or W-track operation and supervises the speed and depth calculations. The unit is effectively a microprocessor operating to a pre-determined program. Actual speed calculation takes place in the correlation block.

The process extracts the time delay by correlating the sampled output of each channel.

The speed unit provides the following outputs to drive both speed and distance counters.

- An analogue voltage, the gradient of which is 0.1 V/knot, to drive the potentiometer servo-type speed indicators.
- A pulse frequency proportional to speed. The frequency is 200/36 pulses/s/knot. Pulses are gated into the digital counter by a 1.8-s gate pulse.
- A positive/negative voltage level to set the ahead/astern indication or the B track/W track indication.
- 2000 pulses per nautical mile to drive the stepping motor in the digital distance indicator.

The depth unit provides the following outputs to drive the depth indicators when the echo sounding facility is used.

- An analogue voltage with a gradient of 0.01Vm^{-1}, to drive the analogue depth indicator.
- Pulses of 2msm^{-1}, which are used to gate a 5 kHz standard frequency into the digital depth indicator.
- A positive/negative voltage level to cause the indicator to display 'normal operation' or 'overrange'.
- When correctly installed and calibrated, a speed accuracy of ±0.1 knot is to be expected. Distance accuracy is quoted as 0.2%. The SAL-ICCOR speed log can be made to measure the vessel's transverse speed with the addition of a second transducer set at 90° to the first.

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3.5 The Doppler principle

In the early 19th century, Christian Doppler observed that the colour emitted by a star in relative movement across the sky appeared to change. Because light waves form part of the frequency spectrum, it was later concluded that the received wavelength must be changing and therefore the apparent received frequency must also change. This phenomenon is widely used in electronics for measuring velocity.

Figure 3.15(b) shows that the wavelength (λ) is compressed in time when received from a transmitter moving towards a receiver (λ_1) and expanded (Figure 3.15c) in time from a transmitter moving away (λ_2). Consider a transmitter radiating a frequency (f_1). The velocity of propagation of radiowaves in free space (c) is 300×10^6 ms^{-1} and in seawater it is much slower at approximately 1500 ms^{-1}. After a period of 1 s, one cycle of the transmitted acoustic wave in seawater will occupy a distance of 1500 m. If the transmitter moves towards an observer at speed (v) it will, at the end of 1 s, have travelled a distance (d) towards the receiver. Each transmitter wave has now been shortened because of the distance travelled by the transmitter towards the observer. By definition, a shorter wavelength defines a higher frequency (f_r). The shortened wavelength, or higher frequency, received is directly proportional to the speed of movement of the transmitter.

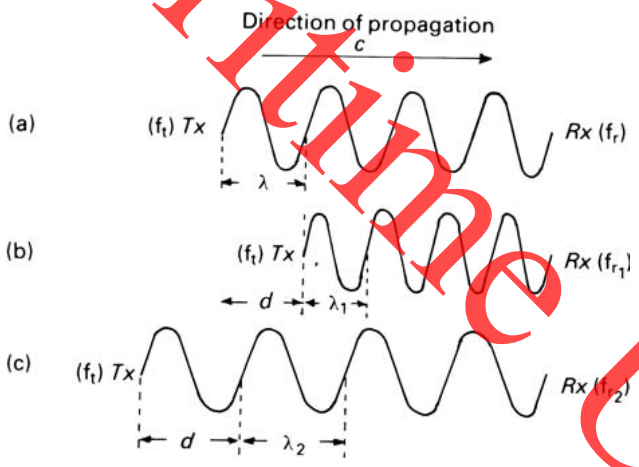

Figure 3.15 Expansion and compression of wavelength.

In Figure 3.15(b), the transmitter has moved towards an observer by a distance (d). This is the distance travelled during the time of generating one cycle (T).

$$T = 1/f \text{ and } d = v \times T = v/f_t$$

Therefore the apparent wavelength is

$$\lambda_1 = \lambda_1 - v/f_t$$

and the frequency is

$$fr_1 = c/\lambda_1 = c/(\lambda_1 - v/f_t) = cf_t/(\lambda ft - v) = cf_t/(c-v)$$

For a moving transmitter that is approaching a receiver, the received frequency is apparently increased. The reverse is true of a transmission from a transmitter moving away from an observer, when the

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wavelength will be stretched and the frequency decreased.

$$\lambda_2 = \lambda + v/f_t$$

$$f_r = f_t c/(c + v)$$

If an observer moves at velocity (v) towards a stationary sound source, the number of cycles reaching the receiver per second is increased, thus the apparent received frequency is increased. The received frequency is

$$f_r = f_r + v/\lambda$$

and

$$1/\lambda = f/c$$

therefore

$$f_t + f_v/c = f_t(1 + v/c) = f_t(c + v)/c$$

If the observer now moves away from the stationary transmitter the apparent received frequency is:

$$f_r = f_t\,(c - v)/c$$

If, as in the Doppler speed log, both the observer and the sound source (transmitter and receiver) are moving towards a reflecting surface, the received frequency is;

$$f_r = f_t \frac{c}{c - v} x \frac{c + v}{c} = f_t \frac{c + v}{c - v}$$

The Doppler frequency shift is

$$f_d = f_r - f_t \text{ (or } f_t - f_r)$$

$$f_d = f_t x \frac{c + v}{c - v} - f_t$$

$$= \frac{cf_t + vf_t - cf_t + vf_t}{c - v}$$

$$= \frac{2vf_t}{c - v}$$

The velocity of radio waves (c) is always far in excess of v and therefore the expression above can be simplified to:

$$f_d = \frac{2vf_t}{c}$$

where f_d = Doppler frequency shift in cycles per second, v = relative speed in the direction of the transmitted wave, f_t = transmitted frequency, and c = velocity of propagation of the radio wave.

3.6 Principles of speed measurement using the Doppler effect

The phenomenon of Doppler frequency shift is often used to measure the speed of a moving object carrying a transmitter. Modern speed logs use this principle to measure the vessel's speed, with respect to the seabed, with an accuracy approaching 0.1%.

If a sonar beam is transmitted ahead of a vessel, the reflected energy wave will have suffered a frequency shift (see Figure 3.16), the amount of which depends upon:

- the transmitted frequency
- the velocity of the sonar energy wave
- the velocity of the transmitter (the ship).

The frequency shift, in hertz, of the returned wave is:

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$$fd = ft - fr$$

where ft = the transmitted wave frequency, and fr = the received wave frequency.

The Doppler shift formula, for a reflected wave, is given as:

$$fd = 2vft/c$$

where v = the velocity of the ship, and c = the velocity of the sonar wave (1500 ms^{-1} in seawater).

Obviously there can be no objects directly ahead of a vessel from which the acoustic wave may be reflected. The wave is therefore transmitted towards the seabed, not vertically as with echo sounding, but ahead at an angle of 60° to the horizontal. This angle has been found to be the optimum angle of incidence with the seabed, which will reflect a signal of sufficient strength to be received by the transducer. The shape of the seabed has no effect on the frequency shift. Provided that the seabed is not perfectly smooth, some energy will be reflected.

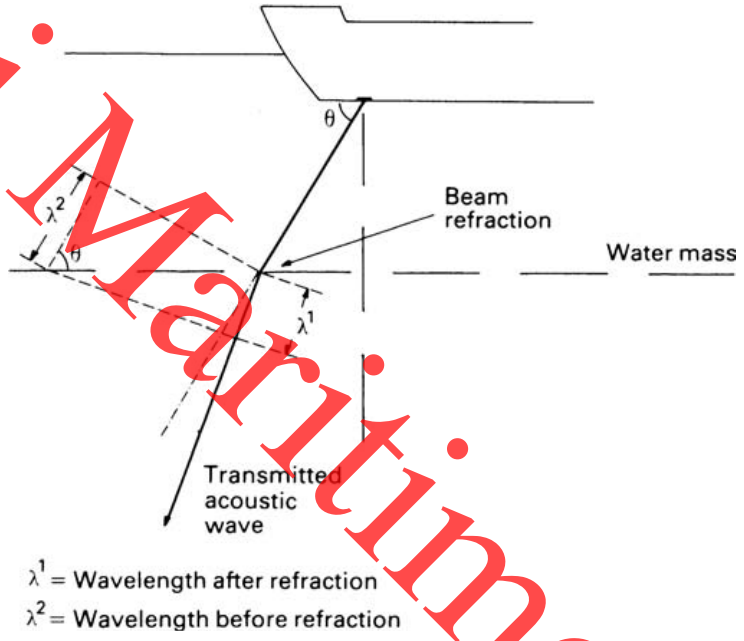

Figure 3.16 Illustration of the change of wavelength that occurs when an acoustic wave crosses a water mass.

The angle between the horizontal plane and the transmission must now be applied to the basic Doppler formula:

$$fd = 2vft\cos\theta/C \text{(in hertz)}$$

Figure 3.17(a) shows this angle. Using trigonometry, cos_ = Adjacent/Hypotenuse. Therefore,

Adjacent = $C\cos\theta$.

Given a propagation angle of 60°, $\cos\theta = 0.5$

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$$fd = 2vft\cos\theta / C = vft/C$$

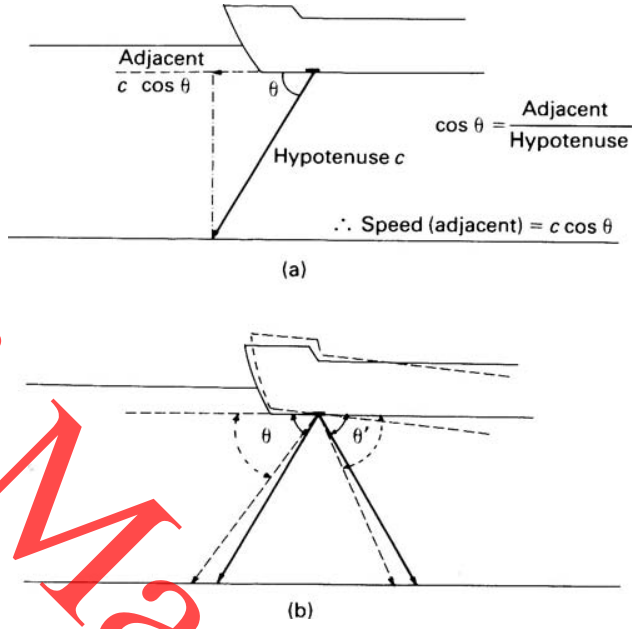

Figure 3.17 (a) Derivation of longitudinal speed using trigonometry. (b) The effect of pitching on a Janus transducer configuration.

It follows that if the angle changes, the speed calculated will be in error because the angle of propagation has been applied to the speed calculation formula in this way. If the vessel is not in correct trim (or pitching in heavy weather) the longitudinal parameters will change and the speed indicated will be in error. To counteract this effect to some extent, two acoustic beams are transmitted, one ahead and one astern. The transducer assembly used for this type of transmission is called a 'Janus' configuration after the Roman god who reputedly possessed two faces and was able to see into both the future and the past. Figure 3.17(b) shows the Janus assembly.

The Doppler frequency shift formula now becomes:

$$fd = \frac{2vft}{C}(+\cos\theta + \cos\theta')$$

(+ cos 60° + cos 60°' = 1) therefore the transmission angle can effectively be ignored.

As Figure 3.17(b) shows, in heavy weather one angle increases as the other decreases effectively cancelling the effects of pitching on the speed indication.

Figure 3.18 shows the advantage of having a Janus configuration over a single transducer arrangement. It can be seen that a 3° change of trim on a vessel in a forward pointing Doppler system will produce a 5% velocity error. With a Janus configuration transducer system, the error is reduced to 0.2% but is not fully eliminated.

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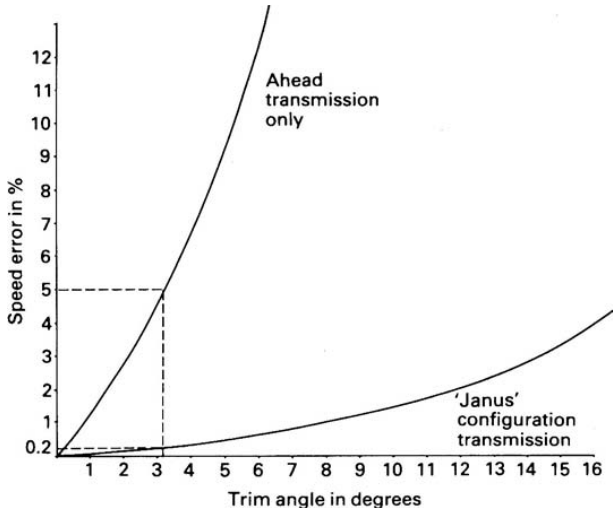

Figure 3.18 Graphs of speed error caused by variations of the vessel's trim.

The addition of a second transducer assembly set at right angles to the first one, enables dual axis speed to be indicated (Figure 3.19).

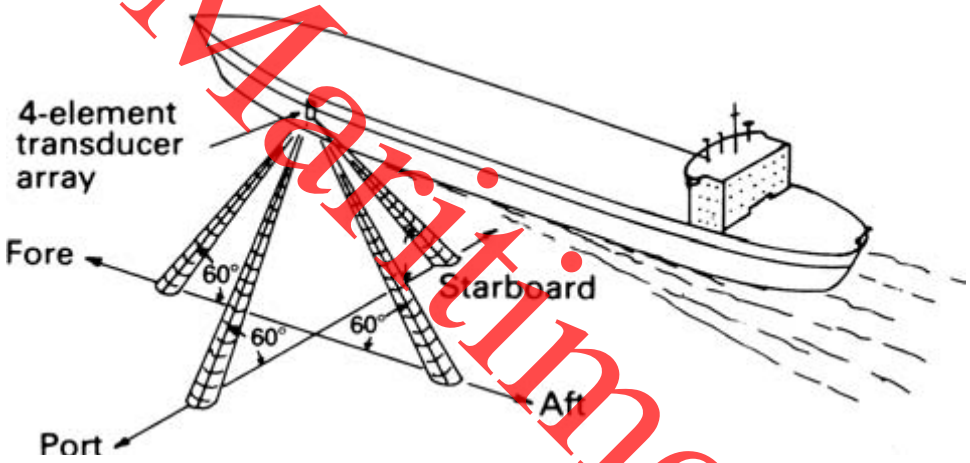

Figure 3.19 Dual axis speed is measured by transmitting sonar pulses in four narrow beams towards the sea bed.

3.6.1 Vessel motion during turn manoeuvres

A precise indication of athwartships speed is particularly important on large vessels where the bow and stern sections may be drifting at different rates during docking or turning manoeuvres.

Speed vectors during a starboard turn

A dual axis Doppler speed log measures longitudinal and transverse speed, at the location of the transducers. If transducers are mounted in the bow and stern of a vessel, the rate of turn can be computed and displayed. This facility is obviously invaluable to the navigator during difficult manoeuvres.

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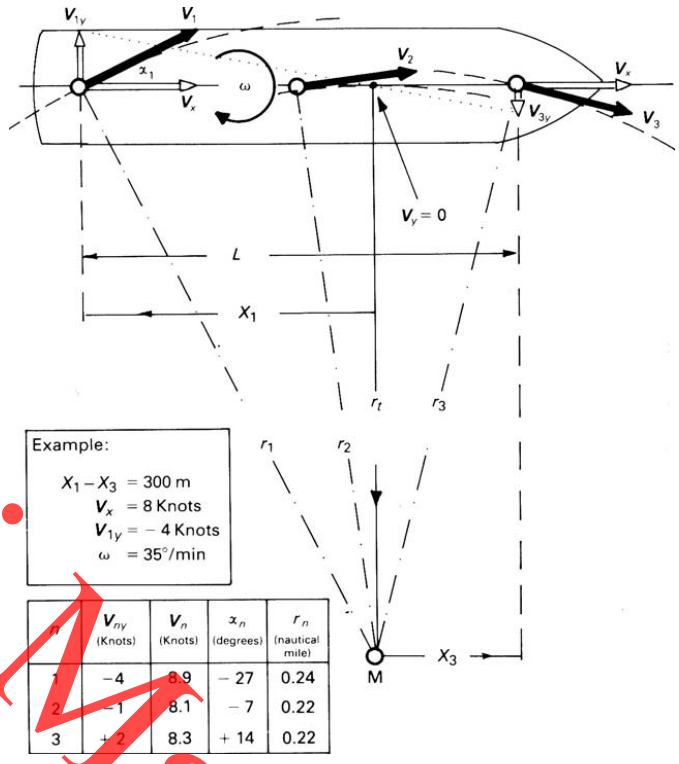

n	V_{ny} (Knots)	V_n (Knots)	α_n (degrees)	r_n (nautical mile)
1	−4	8.9	− 27	0.24
2	−1	8.1	− 7	0.22
3	+ 2	8.3	+ 14	0.22

Figure 3.20 Speed vectors during a starboard turn with no current. (Reproduced courtesy of Krupp Atlas Elektronik.)

Figure 3.20 shows the speed vectors plotted from bow and stern transducer data when a ship is turning to starboard without the effect of water current. When the rudder is put hard over, the transverse speed indication vector (**Vy**) can point either to the side to which the rudder has been moved or to the other side. This will depend upon the longitudinal speed, the angular speed (rate of turn) and weather/tide conditions. If the longitudinal speed and transverse speeds at two points of the vessel are known, the ship's movement is completely determinable. The bow transverse speed vector ($\mathbf{V}_{3y}$) points to starboard, the direction of the ship's turning circle.

Under the influence of the 4-knot current, shown in Figure 3.21, however, $\mathbf{V}_{3y}$ points to port. The transverse speed development along the ship's length is represented by a dotted line (between $\mathbf{V}_{1y}$ and $\mathbf{V}_{3y}$). The intersection of this line with the longitudinal axis produces a point at which the ship has longitudinal speed but no transverse speed. This point ($\mathbf{V}_y = 0$) is normally positioned, approximately, in the fore third of the vessel (see Figure 3.20) if the ship is to turn along a circle about point M (the instantaneous centre of rotation). The effect of current from the starboard side causes point $V_y = 0$ to be ahead of the vessel and the ship to turn around point M in Figure 3.21, which is shifted forward relative to that shown in Figure 3.20. It is obvious therefore that an accurate indication of transverse speeds at various points along the vessel enables the navigator to predict the movement of his ship.

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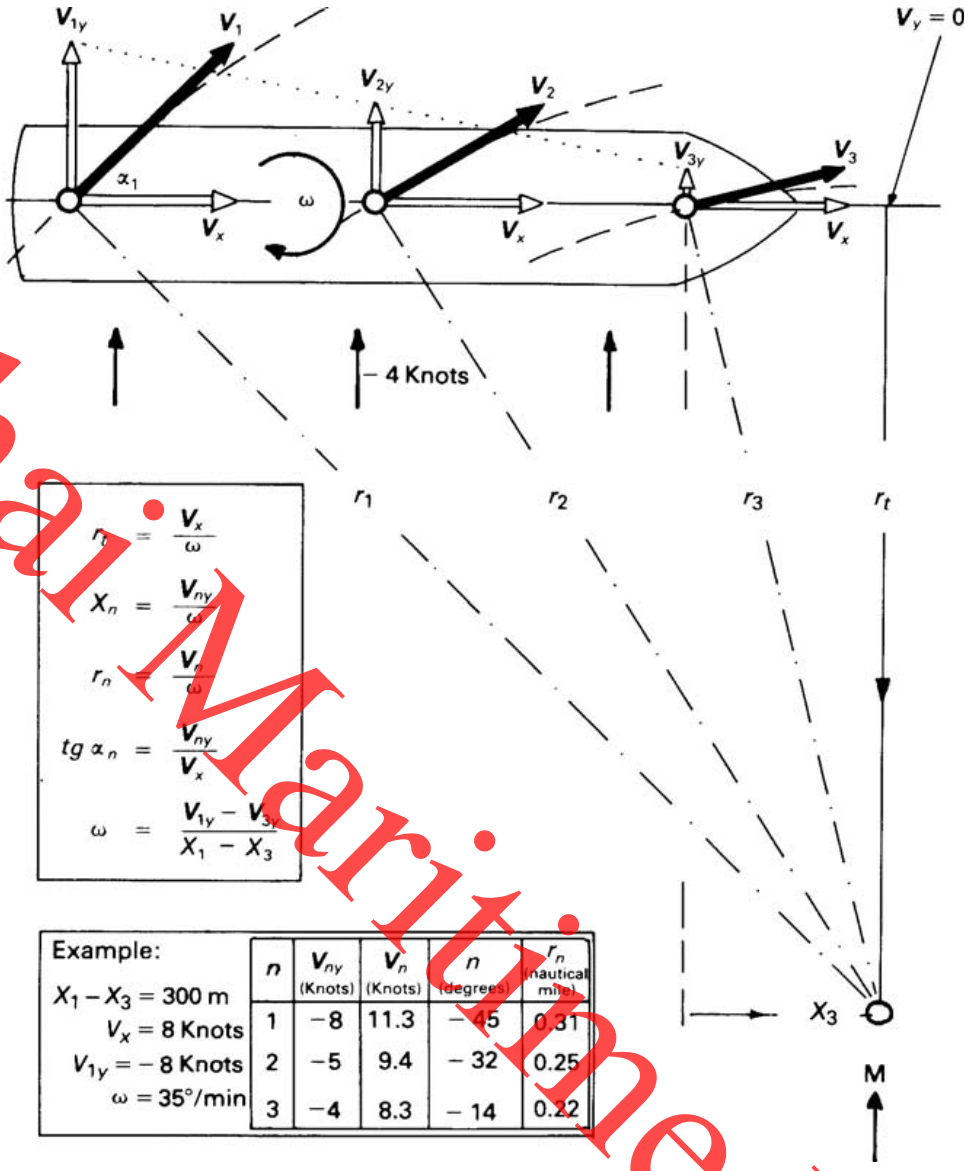

n	V_{ny} (Knots)	V_n (Knots)	n (degrees)	r_n (nautical mile)
1	−8	11.3	− 45	0.31
2	−5	9.4	− 32	0.25
3	−4	8.3	− 14	0.22

Figure 3.21 Speed vectors for a starboard turn under the influence of a four knot current (Reproduced courtesy of Krupp Atlas Elektronik.)

Speed components with the rudder amidships

Dual axis Doppler logs are able to measure accurately the ship's speed in a longitudinal direction ($\mathbf{V}_x$) and a transverse direction ($\mathbf{V}_y$). The data derived from these measurements enables the navigator to predict the course to steer in order to optimize the performance of the vessel. By measuring both speed components (i.e. the velocity vector) it is possible to optimize the vessel's course by computing the drift angle:

$$\propto = \text{arc tan} V_y/V_x$$

In the water-tracking mode this is the leeward angle (caused by wind) which is the angle between the true course (heading) and the course-made-good (CMG) through the water. In the bottom-tracking mode, it is the angle due to wind and tidestream between the heading and the CMG over the ground. With the help of a two-component log the ship can be navigated so that heading steered plus drift angle

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measured by the log, results exactly in the intended chart course (see Figure 3.22).

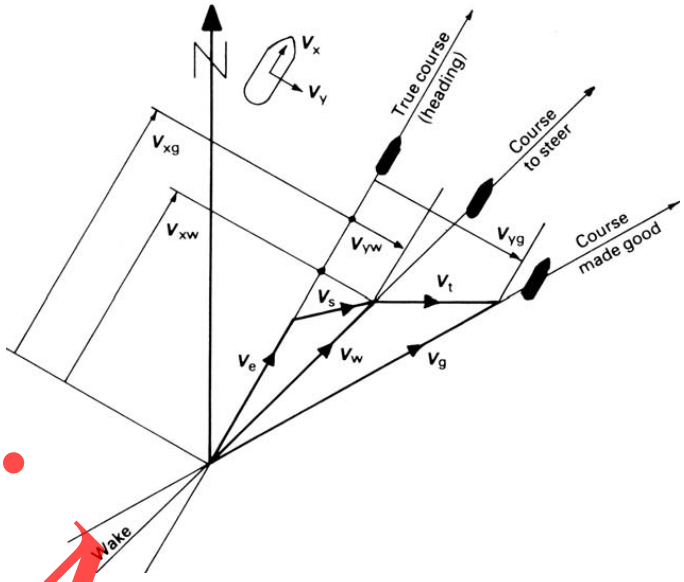

Figure 3.22 External environmental effects of a vessel's track. (Reproduced courtesy of Krupp Atlas Elektronik.)

The transverse speed at the stern is computed from the transverse speed of the bow, the ship's rate of turn and the ship's length as follows:

$$V_{q2} = V_{q1} - \omega L$$

where V_{q2} = stern transverse speed, V_{q1} = bow transverse speed, ω = rate of turn (angular velocity), and

L = distance between bow and stern points of measurement.

3.6.2 Choice of frequency/transducer

As with depth sounding, the size of the transducer can be kept within reasonable limits by using a high frequency. This is particularly important in the situation where many elements are to be mounted in the same assembly. Unfortunately, as has already been discussed, attenuation losses increase exponentially with the transmission frequency. The choice of frequency is therefore a compromise between acceptable transducer size and the power requirements of the acoustic wave in order to overcome the signal losses due to the transmission media. Frequencies used in speed logging systems vary widely and are usually in the range 100 kHz to 1 MHz.

The factor with the greatest effect on speed accuracy is the velocity of the acoustic wave in seawater. Propagation velocity is affected by both the salinity and the temperature of the seawater through which the wave travels. However, velocity error due to these two factors can be virtually eliminated by mounting salinity and temperature sensors in the transducer array. Data from both sensors are processed to provide corrective information for the system. Alternatively, the Krupp Atlas Alpha transducer system effectively counteracts the effects of salinity and temperature by the use of a phased beam.

ALPHA transducer array

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The necessity of a tilted beam normally dictates that the transducer protrudes below the keel and therefore may suffer damage. It is possible to produce the required angle of propagation by the use of a number of flush fitting transducers. The Krupp Atlas Alpha (Atlas Low Frequency Phased Array) multiple transducer 'Janus' assembly uses ($4 \cdot 18 = 72$) flush fitting elements in each of the fore and aft positions. In theory any number of elements may be used, but the spacing of the elements must not exceed certain limits in order to keep unwanted side lobes down to an acceptable level.

Figure 3.23(a) is a cut-away bow section of a vessel fitted with an Alpha transducer array. For clarity, only a three-element assembly is shown. If the three elements are fed with in-phase signal voltages the beam formed would be perpendicular. However, if the signal voltages to each element are phase delayed, in this case by 120°, the main lobe is propagated at an angle (which under these conditions is about 50°). In this case the elements are fed with three sine waves each shifted clockwise by 120°. For the Janus configuration the same elements are fed alternately clockwise and counter clockwise. The Alpha system also overcomes the external factors that influence the velocity of acoustic waves in salt water and is thus able to counteract the unwanted effects of salinity and temperature change.

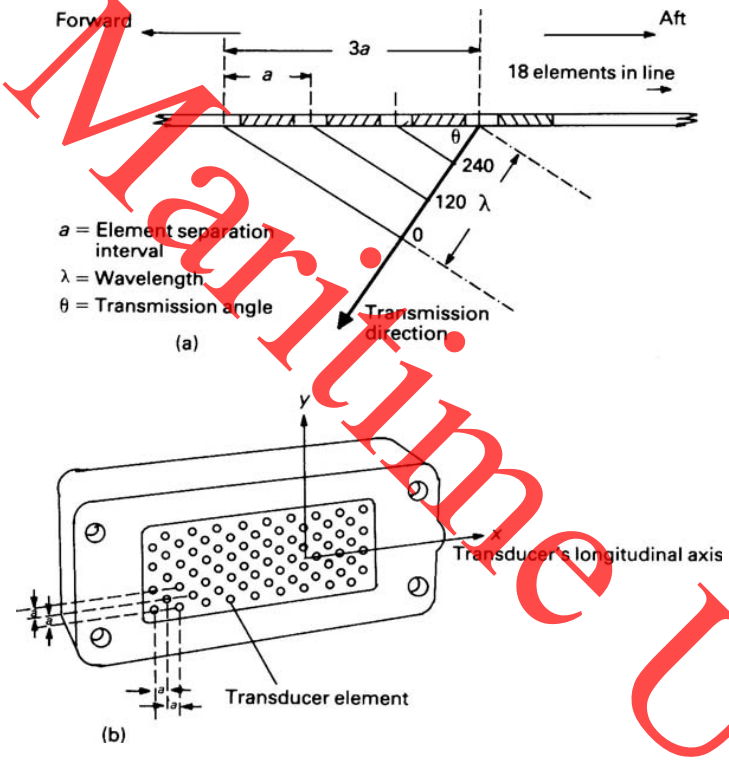

Figure 3.23 (a) Principle of the alpha transducer array. (b) A 72-element alpha transducer array.

The standard Doppler formula, from which velocity is calculated, comprises a number of parameters, two of which are variable. Ideally the vessel's speed (v) should be the only unknown factor in the formula, but unfortunately the velocity of acoustic waves (C) is also a variable. Since speed accuracy depends upon the accuracy of acoustic wave velocity in salt water it is advantageous to eliminate (C) from the formula.

$$fd = 2vft\cos\theta / C$$

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With the Alpha system, the angle of propagation (θ) is a function of the velocity of acoustic waves because of the geometry and mode of activating the multiple elements (see Figure 3.23(a)). The angle of propagation is:

$$\cos\theta = \lambda/3a = C/3a\,ft$$

where a = the transducer element spacing and is therefore a fixed parameter.

$\lambda = C/ft$ = one acoustic wavelength in salt water

If the two earlier equations in this section are now combined, the Doppler frequency shift is:

$$fd = 2v/3a$$

$3a$ is a fixed parameter and therefore v is now the only variable. Two modes of operation are possible.

3.6.3 Choice of transmission mode

Continuous wave mode (CW) transmission

Two transducers are used in each of the Janus positions. A continuous wave of acoustic energy is transmitted by one element and received by the second element. Received energy will have been reflected either from the seabed, or, if the depth exceeds a predetermined figure (20 m is typical), from a water mass below the keel. Problems can arise with CW operation particularly in deep water when the transmitted beam is caused to scatter by an increasing number of particles in the water. Energy due to scattering will be returned to the transducer in addition to the energy returned from the water mass. The receiver is likely to become confused as the returned energy from the water mass becomes weaker due to the increasing effects of scattering. The speed indication is now very erratic and may fall to zero. CW systems are rarely used for this reason.

Pulse mode operation

To overcome the problems of the CW system, a pulse mode operation is used. This is virtually identical to that described previously for depth sounding where a high energy pulse is transmitted with the receiver off. The returned acoustic energy is received by the same transducer element that has been switched to the receive mode. In addition to overcoming the signal loss problem, caused by scattering in the CW system, the pulse mode system has the big advantage that only half the number of transducers is required.

Comparison of the pulse and the CW systems

- Pulse systems are able to operate in the ground reference mode at depths up to 300 m (depending upon the carrier frequency used) and in the water track mode in any depth of water, whereas the CW systems are limited to depths of less than 60 m. However, CW systems are superior in very shallow water, where the pulse system is limited by the pulse repetition frequency (PRF) of the operating cycle.
- The pulse system requires only one transducer (two for the Janus configuration) whereas separate elements are needed for CW operation.
- CW systems are limited by noise due to air bubbles from the vessel's own propeller, particularly when going astern.
- Pulse system accuracy, although slightly inferior to the CW system, is constant for all operating

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depths of water, whereas the accuracy of the CW system is better in shallow water but rapidly reduces as depth increases.

3.6.4 Environmental factors affecting the accuracy of speed logs

Unfortunately environmental factors can introduce errors and/or produce sporadic indications in any system that relies for its operation on the transmission and reception of acoustic waves in salt water.

- *Water clarity.* In exceptional cases the purity of the seawater may lead to insufficient scattering of the acoustic energy and prevent an adequate signal return. It is not likely to be a significant factor because most seawater holds the suspended particles and micro-organisms that adequately scatter an acoustic beam.
- *Aeration*. Aerated water bubbles beneath the transducer face may reflect acoustic energy of sufficient strength to be interpreted erroneously as sea bottom returns producing inaccurate depth indications and reduced speed accuracy. Proper siting of the transducer, away from bow thrusters, for instance, will reduce this error factor.
- *Vessel trim and list.* A change in the vessel's trim from the calibrated normal will affect fore/aft speed indication and an excessive list will affect athwartship speed. A Janus configuration transducer reduces this error.
- *Ocean current profile.* This effect is prevalent in areas with strong tides or ocean currents. In the water track mode, a speed log measures velocity relative to multiple thermocline layers several feet down in the water. If these layers are moving in opposite directions to the surface water, an error may be introduced.
- *Ocean eddy currents.* Whilst most ocean currents produce eddies their effect is minimal. This problem is more likely to be found in restricted waters with big tidal changes or in river mouths.
- *Sea state.* Following seas may result in a change in the speed indication in the fore/aft and/or port/ starboard line depending upon the vector sum of the approaching sea relative to the ship's axis.
- *Temperature profile.* The temperature of the seawater affects the velocity of the propagated acoustic wave (see Figure 2.2 in Chapter 2). Temperature sensors are included in the transducer to produce corrective data that is interfaced with the electronics unit.

3.7 The Furono Doppler Sonar DS-50 System

Another respected manufacturer of marine equipment, Furuno, produces a Doppler sonar system, the DS-30, based on the principles of Doppler speed measurement. Whilst the system principles are the same as with other speed logs in this category, Furuno have made good use of the data processing circuitry and a full colour 10-inch wide LCD display to present a considerable amount of information to a navigator. The display modes or shown in Figure 3.24.

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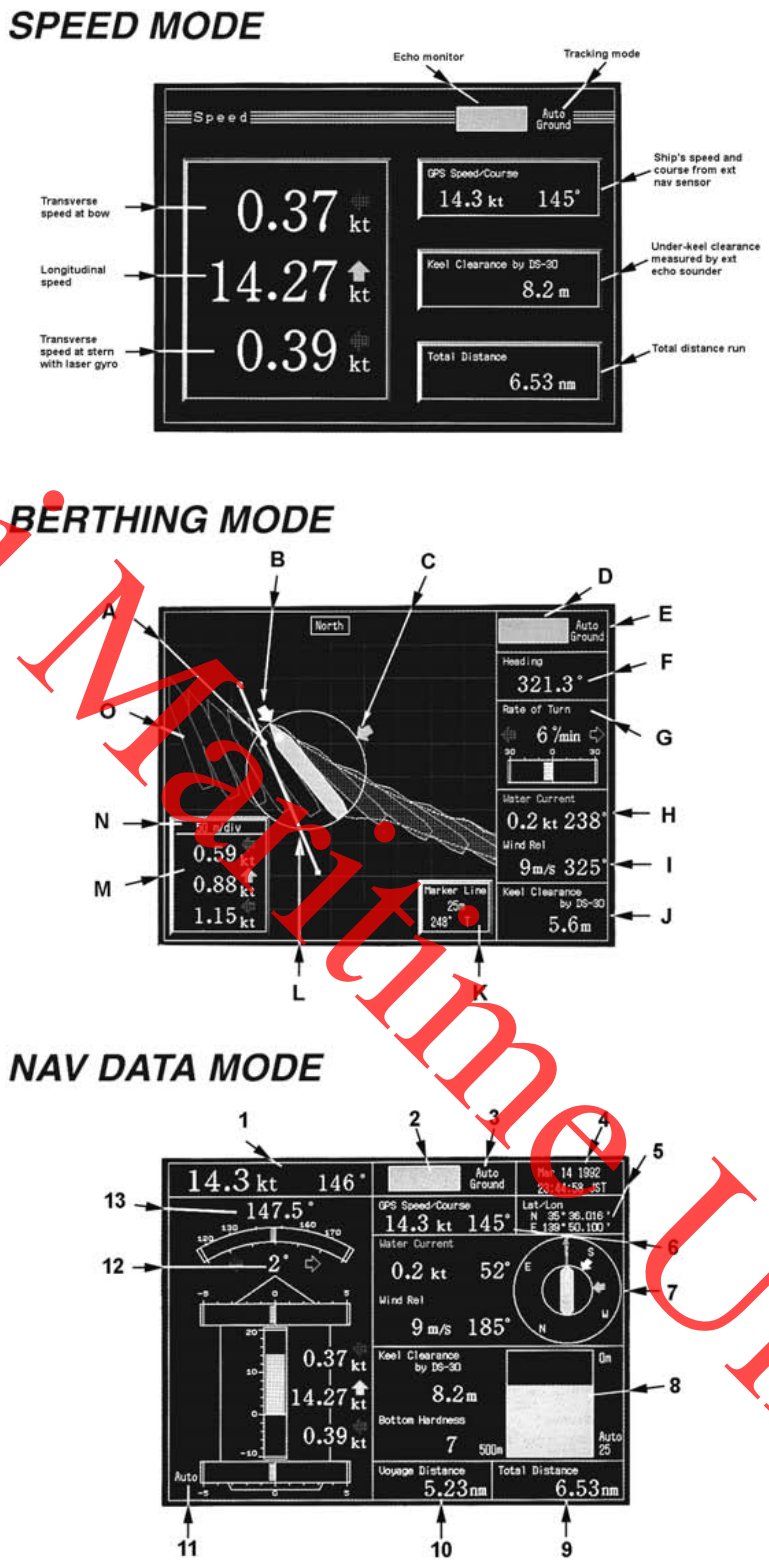

Figure 3.24 Furuno Doppler Sonar DS-30 display modes. (Reproduced courtesy of Furuno Electric Co.)

The system uses a triple beam, 440 kHz pulsed transmission and from the received Doppler shifted signal calculates longitudinal, thwartship speeds and depth beneath the keel at the bow.

In addition, a Laser Gyro may be fitted on the stern to provide a further data input of transverse speed and rate of turn information (see Figures 3.21 and 3.25). Position data from a GPS receiver may also be input to the CPU.

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There are three principle modes of data display.

- The Speed Mode showing all the normal speed/depth/distance indications.
- The Berthing Mode which, with the additional inputs from a laser gyro at the stern, shows a vessel's movements during low speed manoeuvres (see Figure 3.25).
- The Nav Data Mode with a display reminiscent of an integrated navigation system.

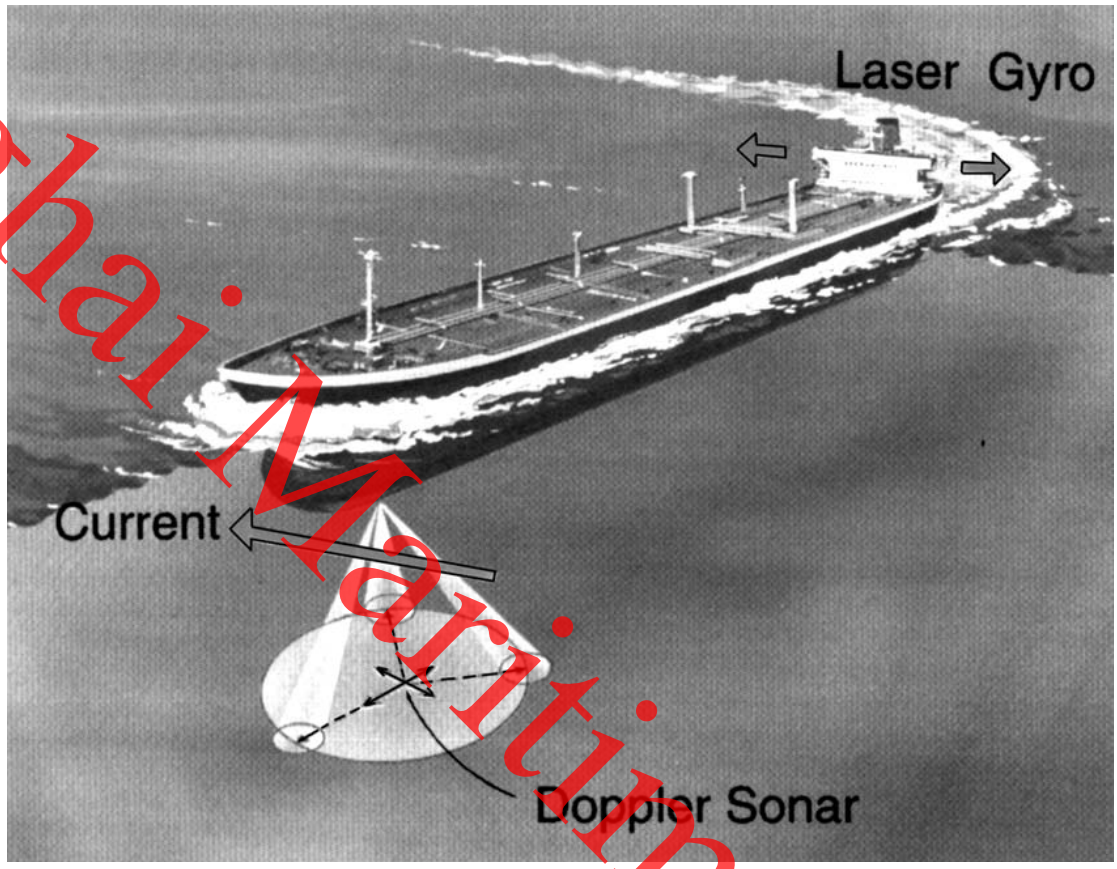

Figure 3.25 Triple beam transducer configuration of the Furuno Doppler Sonar Log. Note the forces acting on the vessel during a starboard turn under the influence of a cross-current from the port side. (Reproduced courtesy of Furuno Electric Co.)

Berthing Mode display

The display diagram key shows the following.

A Intersection of perpendicular from ship's ref. point to marker line.

B Yellow arrowhead showing wind direction.

C Blue arrowhead showing current direction.

D Echo monitor.

E Tracking mode.

F Heading (input from gyro).

G Rate of turn (measured by laser gyro).

H Readout of speed and direction of water current.

I Readout of wind speed and direction (input from wind sensors).

J Under-keel clearance measured by an external echo sounder.

K Range and bearing (true) to marker line.

L Marker line.

M Ship's speed: transverse, longitudinal and transverse at stern with laser gyro.

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N Grid scale and presentation mode.

O Ship's predicted motion.

Nav Data Mode display

The display diagram key for this mode shows the following.

1 Ship's speed and course.

2 Echo monitor.

3 Tracking mode and echo level indicator.

4 Date and time.

5 Position (input from external sensors).

6 Ship's speed and course (input from external sensors).

7 Current speed and direction (app.088°) and wind speed and direction (app. 038°).

8 Graphic presentation of under-keel clearance.

9 Total distance run.

10 Voyage distance from reset.

11 Ship's transverse speed at bow, longitudinal speed and transverse speed at stern with laser gyro.

12 Drift angle (deviation of course over ground from ship's course).

13 Course heading.

3.8 Glossary

Aeration The formation of bubbles on the transducer face causing errors in the system.

ALPHA (Atlas Low Frequency Phased Array) transducer. A flush fitting transducer using multiple elements to create the transmitted beam

Beamwidth The width of the transmitted acoustic pulsed wave. The beam spreads the further it travels away from a transducer.

BITE Built-in test circuitry. A self-test or manually operated diagnostic system.

CW mode Continuous wave transmission. Both the transmitter and receiver are active the whole time. Requires two transducers.

Distance integrator The section of a speed log that produces an indication of distance travelled from speed and time data.

Doppler principle A well-documented natural phenomenon enabling velocity to be calculated from a frequency shift detected between transmission and reception of a radio signal.

E.M. log An electronic logging system relying on the induction of electromagnetic energy in seawater to produce an indication of velocity.

G/T Ground-tracking or ground referenced speed.

NMEA National Marine Electronic Association. Interfacing standards.

Pitot log An electromechanical speed logging system using changing water pressure to indicate velocity.

Pulse mode Acoustic energy is transmitted in the form of pulses similar to an echo sounding device or RADAR

Transducer The transmitter/receiver part of a logging system that is in contact with the water. Similar to an antenna in a communications system.

Translating system The electronic section of a logging system that produces the speed indication from a variety of data.

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W/T Water-tracking or water referenced speed.

3.9 Summary

To be accurate, speed must be calculated with reference to a known datum.

At sea, speed is measured with reference to the ocean floor (ground-tracking (G/T)) or water flowing past the hull (water-tracking (W/T)).

Traditionally, maritime speed logging devices use water pressure, electromagnetic induction, or the transmission of low frequency radio waves as mediums for indicating velocity.

A water pressure speed log, occasionally called a Pitot log:

(a) measures W/T speed only;

(b) requires a complex arrangement of pressure tubes and chambers mounted in the engine room of a ship and a Pitot tube protruding through the hull;

(c) produces a non-linear indication of speed which must be converted to a linear indication to be of any value. This is achieved either mechanically or electrically in the system;

(d) speed indication is affected by the non-linear characteristics of the vessel's hull and by the vessel pitching and rolling;

(e) possesses mechanical sections that require regular maintenance.

An electromagnetic speed log:

(a) measures W/T speed only;

(b) produces a linear speed indication;

(c) operates by inducing a magnetic field in the salt water flowing past the hull and detecting a minute change in the field;

(d) produces a varying speed indication as the conductivity of the seawater changes.

(e) Indication may be affected by the vessel pitching and rolling in heavy weather.

Speed logs that use a frequency or phase shift between a transmitted and the received radio wave generally use a frequency in the range 100–500 kHz. They also use a pulsed transmission format.

A log using the acoustic correlation technique for speed calculation:

(a) can operate in either W/T or G/T mode. G/T speed is also measured with respect to a water mass;

(b) measures a time delay between transmitted and received pulses;

(c) produces a speed indication, the accuracy of which is subject to all the environmental problems affecting the propagation of an acoustic wave into salt water. See Chapter 2.

Doppler frequency shift is a natural phenomenon that has been used for many years to measure velocity. If a transmitter (TX) and receiver (RX) are both stationary, the received signal will be the same frequency as that transmitted. However, if either the TX or the RX move during transmission, then the received frequency will be shifted. If the TX and/or RX move to reduce the distance between them, the wavelength is compressed and the received frequency is increased. The opposite effect occurs if the TX and/or RX move apart.

A Doppler speed logging system:

(a) transmits a frequency (typically 100 kHz) towards the ocean floor and calculates the vessel's speed from the frequency shift detected;

(b) measures both W/T and G/T speed;

(c) produces a speed indication, the accuracy of which is subject to all the environmental problems affecting the propagation of an acoustic wave in salt water;

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(d) uses a Janus transducer arrangement to virtually eliminate the effects of the vessel pitching in heavy weather;
(e) may use more than one transducer arrangement. One at the bow and another at the stern to show vessel movement during turn manoeuvres.

3.10 Revision questions

1 A speed indication is only of value if measured against another parameter. What is the speed indication, produced by a pressure tube speed log, referenced to?
2 What is the approximate velocity of propagated acoustic energy in seawater?
3 In a pressure tube speed logging system, why is the complex system of cones required in the mechanical linkage?
4 What is the speed indication produced by an electromagnetic log referenced to?
5 How does the non-linearity of a ship's hull affect the speed indication produced by an electromagnetic speed log?
6 Does the amount of salinity in the water affect the speed indication produced by an acoustic correlation speed log?
7 Why do all Doppler speed logs use a Janus configuration transducer assembly?
8 How does aeration cause errors in the speed indicated by a Doppler log?
9 Using the $\mathbf{V}_x$ and $\mathbf{V}_y$ speed components produced by a Doppler speed log, how is it possible to predict a vessel's drift rate?
10 Why are pulsed transmission systems used in preference to a continuous wave mode of operation?
11 Why are water temperature sensors included in the transducer assembly of a Doppler speed logging system?
12 How may the distance run be calculated in a speed logging system?

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Chapter 4 The Ship's Magnetic Compass

4.1 Introduction

4. 1 .1 The magnetic compass in the age of electronic navigation

Despite the modern tendency to rely heavily on Electronic Navigational Aids (ENA), the magnetic compass remains a primary navigation instrument on any vessel, and continues to operate independently, *in the not uncommon event of an electrical failure or electronics malfunction.*

Users should be aware that ENA have limitations and have been known to provide erroneous information. Reliable and accessible alternatives for back up and cross reference should always be readily available.

Vessels are required to be equipped with a means of determining direction and heading, readable from the steering position and *independent of any power supply*. A correctly installed and adjusted magnetic compass, of a size and type suitable for the vessel, fulfills this requirement.

There is little doubt that Global Navigation Satellite Systems (GNSS), such as GPS, help to make modern sea travel generally safer and easier than it used to be, particularly when interfaced with A.I.S., radar and electronic chart display systems such as ECDIS. It is, however, worth taking the following into consideration:

- GPS is currently the only fully operational GNSS. It is owned and controlled by the U.S. Department of Defence and its use by commercial shipping is incidental to its primary, military purpose.
- GNSS signals are vulnerable to loss and error, both intentional and unintentional. Malicious jamming of GNSS is a very real threat. GPS signals can be terminated or corrupted by the US military for security purposes.
- Commercial GPS operates on a *single frequency* only. Military GPS receivers operate on a *dual frequency* system which is more reliable and less vulnerable to error caused by atmospheric conditions.
- GNSS signals are extremely vulnerable to solar activity such as *solar flares*. The sun is currently entering a phase of intense solar flare activity which is due to last for several years.
- Some areas of the world, particularly in the higher latitudes, have problematic or no GNSS/GPS coverage.
- Other signal errors, such as *multipath effect*, occur locally when the signal to the antenna is reflected off nearby objects, such as superstructure, masts and funnels.
- Entering the wrong antenna height into the receiver can cause large errors (the difference between a large vessel down on her marks and in ballast is significant).
- Entering the wrong datum can put the vessel's position miles from where it really is. Datum used in GPS calculations is *WGS84*. In some areas of the world electronic chart coverage is by *raster charts* (scanned paper charts) alone. The datum of many raster charts is not WGS84.
- When GPS shows a compass course, it is not showing the ship's heading, it is showing the track of the vessel - where she has been in relation to her current position. With the vessel stationary, GPS will not provide any directional information.

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Figure 1 Failure to observe ENA errors was a major factor in the grounding of this U.S. warship

Most electronic compasses (GPS and gyro compasses are two exceptions) are effected by magnetic deviation. They are also reliant on a power supply. Electronic compasses used for marine navigation, include:

- GPS Compass - comprising 2, or preferably 3, antennas aligned symmetrically fore and aft, will show the ship's heading, in either true or magnetic form, and is normally accurate to within +/- one degree on a steady heading. As with all satellite derived data, it is vulnerable to signal error and reliant on a supply of electricity.
- Fluxgate Compass - uses a number of electrical coils wound on a magnetic core to detect its alignment with the magnetic meridian. It will also detect any other magnetic fields around it and is therefore as susceptible to deviation as the standard compass.
- Electro-Magnetic Resistors - used in some electronic compasses to measure the earth's magnetic field. As the vessel changes direction or alignment with the magnetic meridian, resistance increases or decreases and is interpreted as heading.
- Gyro Compass - usually fitted on larger vessels. It is set to point true north and does not use the earth's magnetic field. It is normally accurate to +/- one or two degrees. Modern fibre optic gyro compasses are continuously corrected by computers, which are updated from GPS. It can take many hours for a gyro compass to operate correctly from the time it is switched on, or switched *back on*, after a power outage.
- Laser and Atomic Compasses - still in early days of development for commercial marine use but may be commonplace in the not too distant future.

In Summary - State of the Art Technology can be a great asset to the modern seafarer - when it works properly. As we all know, it sometimes doesn't, and then things can very quickly turn pear shaped. User error due to inadequate training, fatigue and "information overload" can also contribute to innacuracies and misinterpretation of data. Over reliance on electronic navigation aids leads to complacency and sometimes to disaster.

In recent years, there have been numerous well documented occasions (and many not so well documented) on which a sudden, unexpected loss of power or the undetected inaccuracy of electronic instruments, has rapidly developed into a serious crisis.

Very often, the ability and readiness to switch to old fashioned "manual" navigation, including the use of a reliable magnetic compass (and looking out of the window!), has made the difference between continuing the voyage safely and a major marine incident.

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Figure 2 Over reliance on electronic navigation aids can lead to trouble

4.1.2 Compass location and installation

On most large merchant vessels the standard compass is installed on the "Monkey Island", i.e. above the wheelhouse. It is usually viewed from the helm via a viewing tube, similar to a periscope. Often, electronic repeaters are installed so that compass headings can be viewed around the wheelhouse. Being installed on the highest deck of the ship enables it to be used for taking bearings and keeps it as far away from magnetic interference as possible.

Smaller merchant vessels and warships often have their compass installed inside the wheel house in front of the helm. In a fully enclosed steel wheelhouse a magnetic compass is bound to be affected by a number of deviating magnetic fields and a certain amount of skill is required on the part of the compass adjuster to compensate for these.

Figure 3 Compass installation on the Monkey Island on vessel's centre line

Ideally, the compass should be installed on the vessel's centre line so that deviating magnetic forces are mostly symetrical around the compass. On certain vessels, such as aircraft carriers, some fishing vessels and some modern container ships with a narrow superstructure section, the compass is offset, and this can create interesting challenges for compass adjusters.

On small vessels the compass is usually located in front of the helm position. Care should be taken to ensure the compass is installed far enough away from structural members, equipment and instruments such as radios, speakers, engine rev counters (tachometers), etc, which can produce strong magnetic fields. A few inches one way or the other can sometimes be the difference between major and minor deviation.

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Figure 4 Magnetic compass & electronic instruments in close proximity

It should be installed so it is easily readable from the helm and also accessible for adjusting. A great many modern vessels, particularly luxury motor yachts, have not been designed with this in mind. On one particular sleek, multi-million dollar super yacht, it was found that, in order to access the integral correctors of the flush fitting compass, either the console would need to be partially demolished or the raked wheelhouse windscreen would have to be removed.

Ideally, the compass should be sited so that bearings of objects and other vessels may be taken. This is not always practicable, particularly on smaller vessels, in which case other means of taking bearings should be provided. It should not be forgotten that the compass is a valuable tool in collision avoidance.

Figure 5 Overhead mounted compass

Some vessels have their compass installed in an overhead, deckhead mounted position. A number of manufacturers produce compasses which can be mounted in this fashion. This has an obvious advantage in being easy to read close to eye level. In an "upside down" type, such as that pictured above, it also means that air bubbles in the compass liquid are not such a problem. It is also away from a lot of the deviating magnetic fields often found around a console mounted compass.

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Suffice to say, all fastenings used to install the compass should be of non-ferrous, non-magnetic material, e.g. bronze or marine grade stainless steel.

4.1.3 Variation, deviation and compass correction

MAGNETIC VARIATION (or DECLINATION) is the difference between *True North* and *Magnetic North*. It is due to:

- The earth's magnetic field, which travels from South to North, not travelling in a straight line. In some locations, variation can be in excess of 30 degrees. In some locations it is zero.
- The Magnetic North and South Poles being located considerable distances from the Geographic North and South Poles respectively. (The Magnetic North Pole is over 1,000 miles from the Geographic North Pole and this distance is currently increasing by about 40 miles a year).

The compass is said to be pointing magnetic north when it is perfectly aligned with the earth's magnetic field - along the magnetic meridian. Therefore, the direction of magnetic north will vary between zero degrees and in excess of 30 degrees to east or west of true north, depending on the location.

COMPASS DEVIATION is the difference between magnetic north and the direction in which the compass is pointing. Both variation and deviation are measured in degrees east (+) or west (-).

Easterly deviation should be added to the compass heading to give the magnetic heading and westerly deviation should be subtracted.

Remember: "ERROR EAST - COMPASS LEAST"

Similarly, easterly variation must be added to the magnetic heading to give the true heading and westerly variation must be subtracted.

CAUSES OF DEVIATION - All vessels have numerous magnetic fields. Some of these fields are permanently built into the structure of the vessel and some are caused by the type of cargo carried, electronic instruments, position of machinery and equipment, etc.

Figure 6 Some cargoes may affect the magnetic compass more than others

These magnetic fields can combine to cause the compass needle to point away, or *deviate*, from magnetic north. The amount of deviation can vary considerably from heading to heading as the vessel's magnetism is influenced by the earth's own. The vessel's *soft iron* magnetism changes with the orientation and location of the vessel and is known as *induced* magnetism. *Hard iron* magnetism remains constant, is built into the vessel and is known as *permanent* magnetism.

The aim of the compass adjuster is to nullify the effect of the unwanted magnetic fields by placing *compensating magnets* and *soft iron correctors* adjacent to the compass. These create equal but opposing magnetic fields, thus eliminating the deviating fields around the compass, enabling it to align correctly. Each axis, vertical, longitudinal and athwartships is treated seperately.

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4.1.4 Swinging the compass

Swinging the compass, or *swinging the ship* as the operation is sometimes called, typically involves taking the vessel to a suitable location and, with the vessel steady on each of the eight primary compass points, comparing the difference between existing compass headings or bearings with what we know the actual magnetic headings or bearings should be, the difference being the deviation.

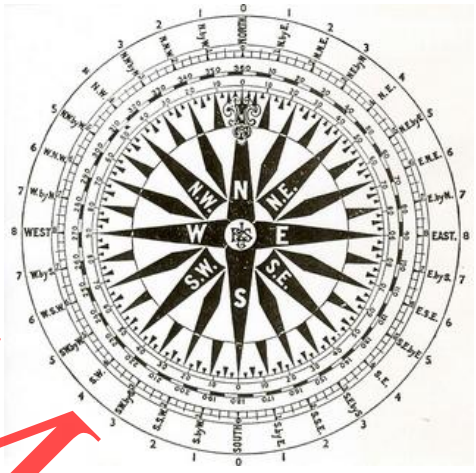

Figure 7 Compass Card

During the process, any magnetic fields, created by the ship's structure, equipment, etc, which cause the compass to deviate are reduced or, if possible, eliminated, by creating equal but opposite magnetic fields using compensating correctors. These are placed inside the compass binnacle or adjacent to the compass:

- Magnets are aligned fore and aft and athwartships to create horizontal magnetic fields to compensate for the *permanent horizontal components* of the ship's magnetism.
- Soft iron correcting spheres or plates and the Flinders bar compensate for the *induced* magnetism caused by the effect the earth's magnetic field has on the ship's magnetism.
- Heeling error magnets compensate for the *vertical component* of the ship's magnetism.

The timing and logistics of this operation are often governed by the tide, the weather and other vessels in the vicinity. The time it takes to swing and adjust the compass is also influenced by the condition and accessibility of the compass and correctors, the manoeuvrability of the vessel, the skill of the helmsman and the complexity of, and reasons for, the deviating magnetic fields involved.

On successful completion of compass swing, a table recording any remaining residual deviation and a statement as to the good working order of the compass will be issued. A current deviation card / certificate of adjustment is a legal requirement on all sea going commercial vessels.

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Figure 8 Using a shadow pin and the sun to check the compass for deviation

Deviation can be determined by a number of methods: the sun's azimuth or known bearings of distant objects, such as a mountain peak or lighthouse are considered most accurate. In certain circumstances, such as poor visibility, comparisons with other navigation instruments, such as a gyro or GPS compass, are sometimes made.

Using other navigation instruments to find deviation is only satisfactory if the absolute accuracy of these instruments has first been verified, or any known error is factored into the calculations. Most professionals prefer something tangible, such as a fixed landmark, with a known position and bearing to work with.

GPS compasses are normally accurate to within a degree or so with the vessel on a steady heading but are often useless on a swinging vessel. All navigation instruments, whether portable or fixed, including GPS compasses, should themselves be checked for error each time they are used for calibrating a magnetic compass.

Figure 9 Signal flags "OSCAR" over "QUEBEC" - Denotes swinging the ship

It should be noted that the compass cannot be adjusted to any degree of verifiable accuracy with the vessel alongside. Deviation must be observed and required adjustments made with the ship's head steady on numerous headings. This requires the vessel to be in open water, clear of other vessels and away from magnetic interferences such as cranes, steel piles, reinforced concrete jetties, etc.

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Some preliminary adjustments, based on a detailed analysis of compass deviation history (if available), may be made prior to sailing. Other adjustments, if made with the vessel alongside, will be largely based on guess work and cannot be relied upon until the compass has been fully swung. The compass adjuster must be on board the vessel for the compass swing!

A few compass adjusters will claim that, because of their "expertise", there is no need for them to go to the trouble of swinging the ship. Large discrepancies between actual deviation and that "predicted" by the adjuster, sometimes as much as 30 degrees, have been observed on compasses which have been "expertly adjusted" without swinging the compass. A valid deviation card cannot be issued until the compass has been properly swung.

4. 1.5 The period the compass shall be swung

Over a period of time, or after certain events, the vessel's magnetic fields may change, altering the residual deviation of the compass. In some circumstances the changes can be quite dramatic. New steel vessels will have their compass adjusted when first commissioned. It is not unusual for a one or two year old vessel to record deviation of 30 to 40 degrees as the residual magnetic fields created during the building process gradually dissipate.

Sea going vessels are required to observe and record compass deviation daily whilst on passage. These observations are important, not only for safe navigation, but also to assist the compass adjuster in making an accurate analysis of the causes of deviation, should the compass require adjustment.

Many maritime authorities and organisations, including the US Coastguard, stipulate that the magnetic compass is to be swung and adjusted annually. Prudent mariners and vessel operators will always ensure that the compass is regularly checked and properly adjusted.

Merchant vessels are often subject to costly detentions by Port State Control authorities should they fail to maintain a record of deviation observations or the compass is found to have deviation in excess of 5 degrees.

Any vessel operating under state survey is required to have its magnetic compass examined and adjusted by an approved compass adjuster at maximum three yearly intervals.

In addition to regular routine checking of the compass for deviation, and adjustment for survey compliance, all sea going vessels should have their compass inspected, swung and adjusted, and a new deviation card issued, when any of the following apply:

- After periods of lay up
- When a new compass is installed
- When deviation exceeds 5 degrees
- On a new vessel or in a new area of operation
- After trauma, such as lightning strike, grounding, fire, etc
- When compass performance is unsatisfactory or unreliable
- When a record of compass deviation has not been maintained
- After alterations and additions to vessel's structure and equipment
- After repairs involving welding, cutting, grinding, etc which may affect the compass
- When electrical or magnetic equipment close to the compass is added, removed or altered
- When compass deviation does not appear to correspond with that shown on deviation card

4. 1.6 A Compass card tilts

The earth's magnetic field travels from the Magnetic South Pole to the Magnetic North Pole. For the sake of mathamatical convenience it is divided into two major components: vertical and horizontal. The

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closer to the poles, the stronger the vertical component and the weaker the horizontal component. At the magnetic equator the horizontal component is at its strongest and the vertical component is zero.

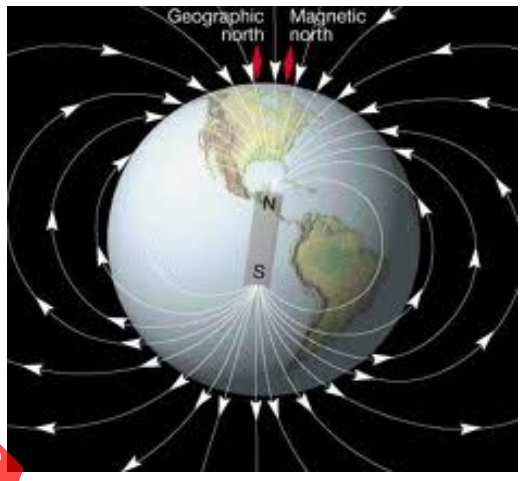

Figure 10 The earth magnetism filed

In the south, the magnetic field comes up, out of the earth and in the north, it goes back down, into the earth. As the compass needle is integral with the card of a marine compass, the upwards or downwards magnetic force can affect the needle and cause the compass card to tilt. The closer to the poles, the stronger the upwards or downwards force and the greater the tilt. To counter this, the card has a small counter-weight attached to enable it to sit level.

A boat compass specifically designed for Northern Hemisphere use will have a weight positioned to counter the downward magnetic force. When this compass is brought to the Southern Hemisphere, the combination of the weight and the upwards magnetic force will create an exagerated tilt on the card. Obviously, the same thing will happen to a Southern Hemisphere compass when it goes to the north.

Rebalancing the compass for the opposite hemisphere involves dismantling the compass and moving the weight to the opposite side of the card and is not usually considered economically viable. For a yacht travelling between the higher latitudes of one hemisphere to the other, carrying two interchangable compasses, one balanced for each hemisphere might be advisable.

Other reasons for compass card tilt:

- Heeling error magnets require adjustment
- Damaged card float chamber
- Damaged jewel pivot
- Card dislodged from pivot
- Low liquid / fluid level

4. 1.7 A professional compass adjuster

Effective correction, or compensation, of the marine compass for any deviation error found during the compass swing requires an understanding of the earth's and ship's magnetic fields and an ability to differentiate between the *permanent magnetism* of the ship's *hard iron* and the *induced magnetism* of the ship's *soft iron*.

It is necessary to recognise the effect the various magnetic fields have on the ship's compass and to have a practical knowledge of the workings of the marine compass and its correctors. Simply reducing or eliminating compass deviation on a vessel in one location can actually make it worse when the vessel travels to another location, particularly when substantial changes in latitude are involved.

Whilst amateur or DIY compass adjusting is not a completely outrageous concept on pleasure craft, it

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has been known to transform a relatively simple problem into a fairly complex one, particularly on steel vessels.

Most licensed compass adjusters are highly skilled technicians, professional seafarers and qualified navigators who have undertaken rigorous and comprehensive training to meet national and international standards.

National marine agencies specify that commercial vessels have their compass adjusted only by a person qualified and authorised to do so. International standards for magnetic compasses and compass adjusting are governed by the International Organization for Standardization (ISO) and the International Maritime Organization (IMO) SOLAS 74 Convention.

4. 1.8 Compass liquid

From time to time an air bubble may appear in the damping liquid in the bowl of a marine compass. This is often a result of leakage around the seals between the bowl and the diaphram or the glass. Sometimes it indicates damage to the bowl or diaphram. A small bubble will not in itself affect the performance of the compass but may partially obscure the compass card. A larger bubble can have an adverse effect on performance.

Removing the bubble requires some patience as it is necessary to replace the air with liquid. Some modern, cheaper compasses are sealed units and cannot be refilled. If the compass is refillable and is leaking a lot of liquid, an attempt at repairing might be made before refilling. Often, particularly in the case of small cheaper compasses, purchasing a new compass is found to be the most economical option.

Finding the correct liquid/fluid for the compass can be a problem. It can be one, or a mixture, of several ingredients. Different manufacturers use different ingredients and some are not compatible with others. Some are not compatible with the compass and can remove the paint and markings from the compass card or cause other damage. Some are oil based, some are water/spirit based.

The safest option is to obtain the correct liquid from the manufacturer. Unfortunately this can be difficult. Some chandlers will stock "compass liquid" but the ingredients of this are often unknown. If the required ingredients can be determined, it may be possible to obtain suitable liquid from local sources, at a much cheaper rate.

To check compatibility, draw some existing liquid out of the bowl with a syringe and mix with the new liquid. It will often be immediately obvious if it is not compatible.

The following are some of the main types of compass liquid ingredients:

- Ethyl alcohol (ethanol) / distilled water
- Isopropanol (rubbing alcohol) / distilled water
- Kerosene (paraffin oil)
- Silicon oil
- Mineral oil

4.2 Magnetism

4.2.1 The magnetic compass

The principle of the present day magnetic compass is in no way different from that of the compass used by the ancients. It consists of a magnetized needle, or array of needles, pivoted so that rotation is in a horizontal plane. The superiority of the present day compass results from a better knowledge of the laws of magnetism, which govern the behavior of the compass, and from greater precision in

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construction.

4.2.2 Magnetism

Any piece of metal on becoming magnetized, that is, acquiring the property of attracting small particles of iron or steel, will assume regions of concentrated magnetism, called poles. Any such magnet will have at least two poles, of unlike polarity. Magnetic lines of force (flux) connect one pole of such a magnet with the other pole as indicated in Figure 11. The number of such lines per unit area represents the intensity of the magnetic field in that area. If two such magnetic bars or magnets are placed side by side, the like poles will repel each other and the unlike poles will attract each other.

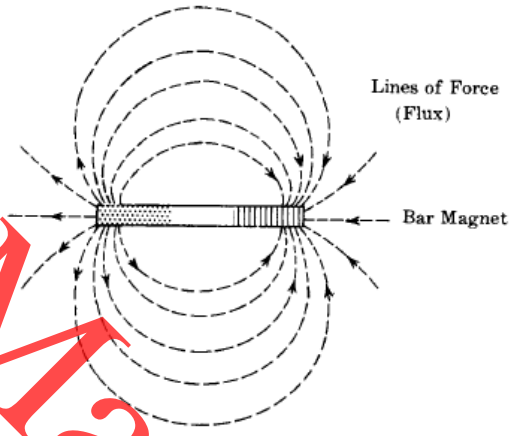

Figure 11 Lines of magnetic force about a magnet

Magnetism is in general of two types, permanent and induced. A bar having permanent magnetism will retain its magnetism when it is removed from the magnetizing field. A bar having induced magnetism will lose its magnetism when removed from the magnetizing field. Whether or not a bar will retain its magnetism on removal from the magnetizing field will depend on the strength of that field, the degree of hardness of the iron (retentivity), and also upon the amount of physical stress applied to the bar while in the magnetizing field. The harder the iron the more permanent will be the magnetism acquired.

4.2.3 Terrestrial magnetism

The accepted theory of terrestrial magnetism considers the earth as a huge magnet surrounded by lines of magnetic force that connect its two magnetic poles. These magnetic poles are near, but not coincidental, with the geographic poles of the earth. Since the north-seeking end of a compass needle is conventionally called a red pole, north pole, or positive pole, it must therefore be attracted to a pole of opposite polarity, or to a blue pole, south pole, or negative pole.

The magnetic pole near the north geographic pole is therefore a blue pole, south pole, or negative pole; and the magnetic pole near the south geographic pole is a red pole, north pole, or positive pole.

Figure 12 illustrates the earth and its surrounding magnetic field. The flux lines enter the surface of the earth at different angles to the horizontal, at different magnetic latitudes. This angle is called the angle of magnetic dip, θ, and increases from zero, at the magnetic equator, to 90° at the magnetic poles. The total magnetic field is generally considered as having two components, namely H, the horizontal component, and Z, the vertical component. These components change as the angle θ changes such that H is maximum at the magnetic equator and decreases in the direction of either pole; Z is zero at the magnetic equator and increases in the direction of either pole.

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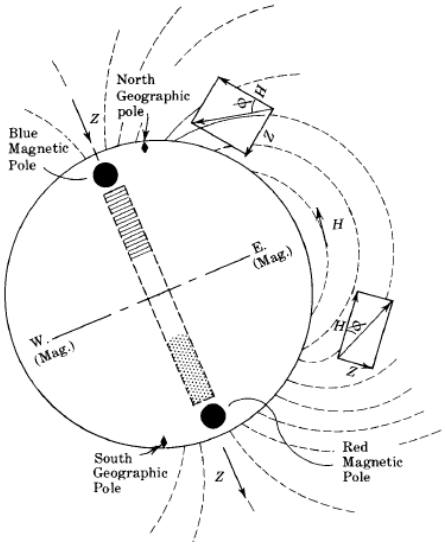

Figure 12 Terrestrial magnetism

Inasmuch as the magnetic poles of the earth are not coincidental with the geographic poles, it is evident that a compass needle in line with the earth's magnetic field will not indicate true north, but magnetic north. The angular difference between the true meridian (great circle connecting the geographic poles) and the magnetic meridian (direction of the lines of magnetic flux) is called variation. This variation has different values at different locations on the earth. These values of magnetic variation may be found on the compass rose of navigational charts. The variation for most given areas undergoes an annual change, the amount of which is also noted on all charts. See Figure 13.

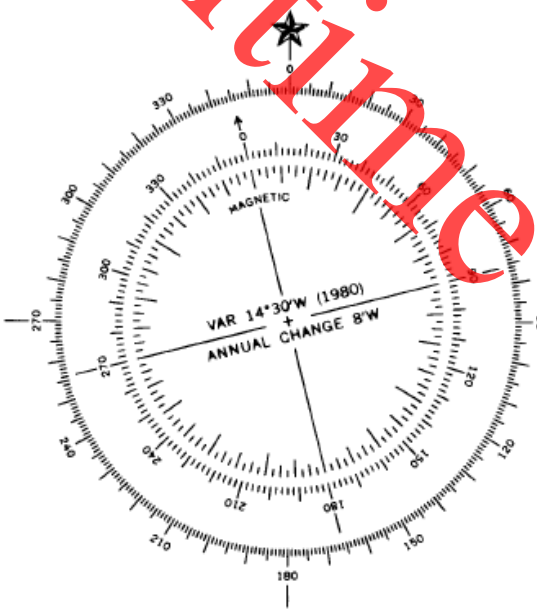

Figure 13 Compass rose showing variation and annual change

4.2.4 Ship's magnetism

A ship, while in the process of being constructed, will acquire magnetism of a permanent nature under the extensive hammering it receives in the earth's magnetic field. After launching, the ship will lose some of this original magnetism as a result of vibration, pounding, etc., in varying magnetic fields, and will eventually reach a more or less stable magnetic condition. This magnetism which remains is the permanent magnetism of the ship.

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The fact that a ship has permanent magnetism does not mean that it cannot also acquire induced magnetism when placed in a magnetic field such as the earth's field. The amount of magnetism induced in any given piece of soft iron is dependent upon the field intensity, the alignment of the soft iron in that field, and the physical properties and dimensions of the iron.

This induced magnetism may add to or subtract from the permanent magnetism already present in the ship, depending on how the ship is aligned in the magnetic field. The softer the iron, the more readily it will be induced by the earth's magnetic field and the more readily it will give up its magnetism when removed from that field.

The magnetism in the various structures of a ship which tends to change as a result of cruising, vibration, or aging, but does not alter immediately so as to be properly termed induced magnetism, is called subpermanent magnetism. This magnetism, at any instant, is recognized as part of the ship's permanent magnetism, and consequently must be corrected as such by means of permanent magnet correctors. This subpermanent magnetism is the principal cause of deviation changes on a magnetic compass. Subsequent reference to permanent magnetism in this text will refer to the apparent permanent magnetism that includes the existing permanent and subpermanent magnetism at any given instant.

A ship, then, has a combination of permanent, subpermanent, and induced magnetism, since its metal structures are of varying degrees of hardness. Thus, the apparent permanent magnetic condition of the ship is subject to change from deperming, excessive shocks, welding, vibration, etc.; and the induced magnetism of the ship will vary with the strength of the earth's magnetic field at different magnetic latitudes, and with the alignment of the ship in that field.

4.2.5 Resultant induced magnetism from earth's magnetic field

The above discussion of induced magnetism and terrestrial magnetism leads to the following facts. A long thin rod of soft iron in a plane parallel to the earth's horizontal magnetic field, *H*, will have a red (north) pole induced in the end toward the north geographic pole and a blue (south) pole induced in the end toward the south geographic pole. This same rod in a horizontal plane but at right angles to the horizontal earth's field would have no magnetism induced in it, because its alignment in the magnetic field is such that there will be no tendency toward linear magnetization and the rod is of negligible cross section. Should the rod be aligned in some horizontal direction between those headings that create maximum and zero induction, it would be induced by an amount that is a function of the angle of alignment. If a similar rod is placed in a vertical position in northern latitudes so as to be aligned with the vertical earth's field *Z*, it will have a blue (south) pole induced at the upper end and a red (north) pole induced at the lower end. These polarities of vertical induced magnetization will be reversed in southern latitudes. The amount of horizontal or vertical induction in such rods, or in ships whose construction is equivalent to combinations of such rods, will vary with the intensity of *H* and *Z*, heading, and heel of the ship.

4.3 Theory of magnetic compass adjustment

4.3.1 Magnetic adjustment

The magnetic compass, when used on a steel ship, must be so corrected for the ship's magnetic conditions that its operation approximates that of a nonmagnetic ship. Ship's magnetic conditions create deviations of the magnetic compass as well as sectors of sluggishness and unsteadiness. Deviation is defined as deflection of the card (needles) to the right or left of the magnetic meridian. Adjustment of

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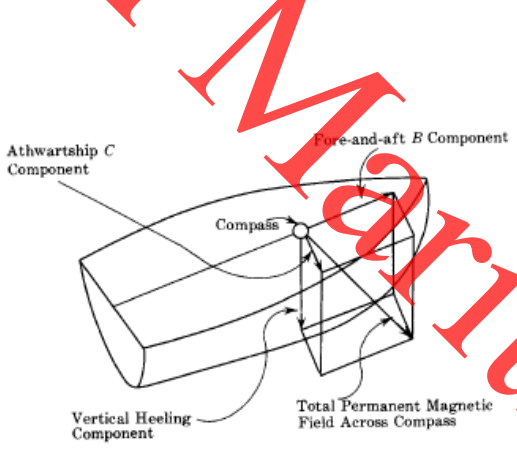
the compass is the arranging of magnetic and soft iron correctors about the binnacle so that their effects are equal and opposite to the effects of the magnetic material in the ship, thus reducing the deviations and eliminating the sectors of sluggishness and unsteadiness. The magnetic conditions in a ship which affect a magnetic compass are permanent magnetism and induced magnetism.

4.3.2 Permanent magnetism and its effects on the compass

The total permanent magnetic field effect at the compass may be broken into three components mutually 90° apart, as shown in Figure 14(a). The effect of the vertical permanent component is the tendency to tilt the compass card and, in the event of rolling or pitching of the ship to create oscillating deflections of the card. Oscillation effects that accompany roll are maximum on north and south compass headings, and those that accompany pitch are maximum on east and west compass headings. The horizontal *B* and *C* components of permanent magnetism cause varying deviations of the compass as the ship swings in heading on an even keel. Plotting these deviations against compass heading will produce sine and cosine curves, as shown in Figure 14(b). These deviation curves are called semicircular curves because they reverse direction in 180°.



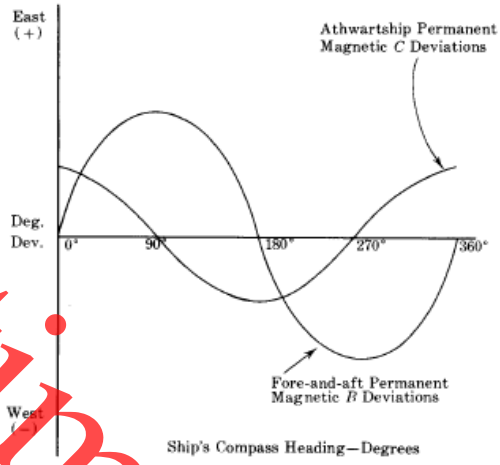


Figure 14(a) Components of permanent magnetic field Figure 14(b) Permanent magnetic deviation effects

The permanent magnetic semicircular deviations can be illustrated by a series of simple sketches, representing a ship on successive compass headings, as in Figures 15(a) and 15(b). The ships illustrated in Figures 15(a) and 15(b) are pictured on cardinal compass headings rather than on cardinal magnetic headings, for two reasons: (1) Deviations on compass headings are essential in order to represent sinusoidal curves that can be analyzed mathematically. This can be visualized by noting that the ship's component magnetic fields are either in line with or perpendicular to the compass needles only on cardinal compass headings. (2) Such a presentation illustrates the fact that the compass card tends to float in a fixed position, in line with the magnetic meridian. Deviations of the card to right or left (east or west) of the magnetic meridian result from the movement of the ship and its magnetic fields about the compass card.

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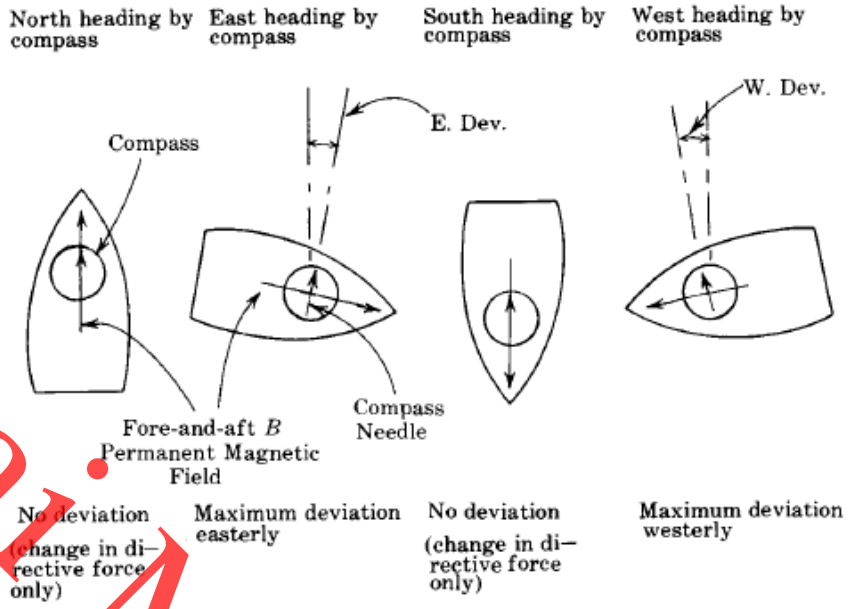

Figure 15(a) Force diagrams for fore-and-aft permanent *B* magnetic field

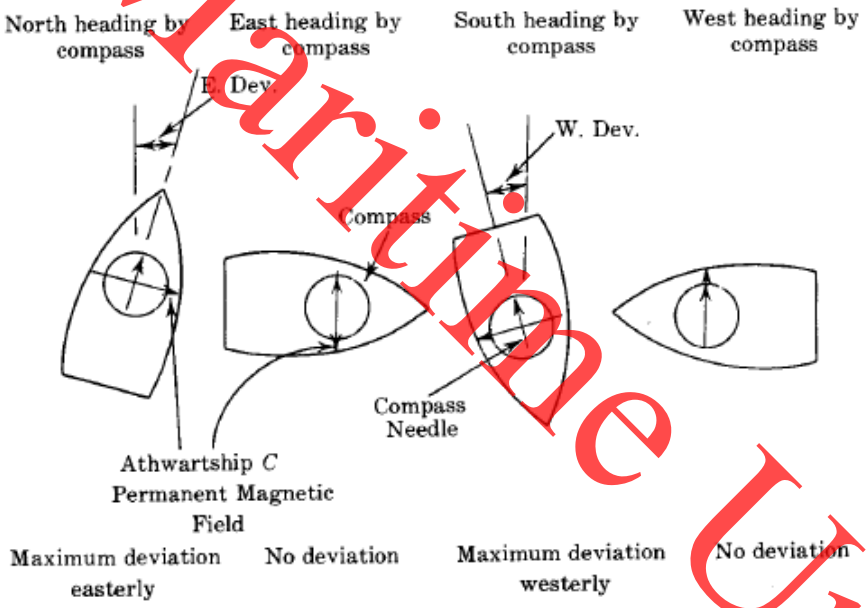

Figure 15(b) – Force diagrams for athwartship permanent *C* magnetic field

Inasmuch as a compass deviation is caused by the existence of a force at the compass that is superimposed upon the normal earth's directive force, *H*, a vector analysis is helpful in determining deviations or the strength of deviating fields. For example, a ship as shown in Figure 16 on an east magnetic heading will subject its compass to a combination of magnetic effects; namely, the earth's horizontal field *H*, and the deviating field *B*, at right angles to the field *H*. The compass needle will align itself in the resultant field which is represented by the vector sum of *H* and *B*, as shown. A similar analysis on the ship in Figure 16 will reveal that the resulting directive force at the compass would be maximum on a north heading and minimum on a south heading, the deviations being zero for both conditions. The magnitude of the deviation caused by the permanent *B* magnetic field will vary with different values of *H*; hence, deviations resulting from permanent magnetic fields will vary with the magnetic latitude of the ship.

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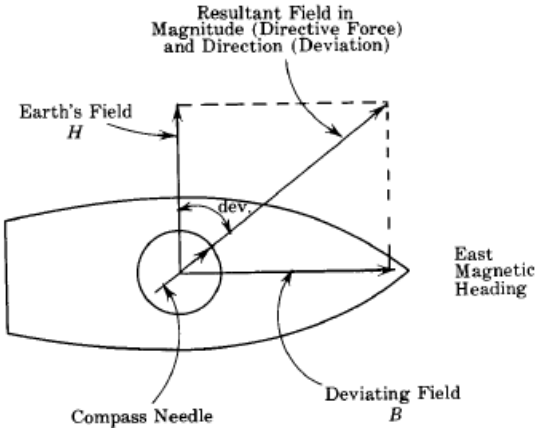
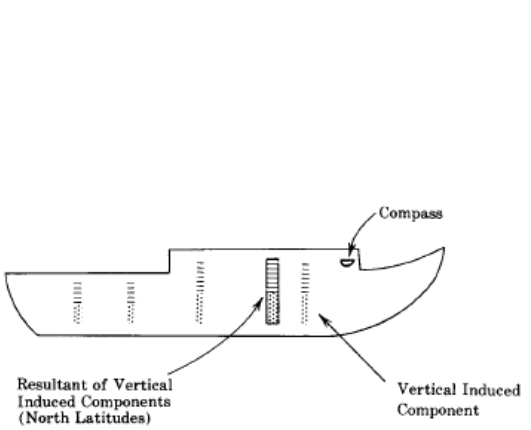


Figure 16 General force diagram

4.3.3 Induced magnetism and its effects on the compass

Induced magnetism varies with the strength of the surrounding field, the mass of metal, and the alignment of the metal in the field. Since the intensity of the earth's magnetic field varies over the earth's surface, the induced magnetism in a ship will vary with latitude, heading, and heel of the ship.

With the ship on an even keel, the resultant vertical induced magnetism, if not directed through the compass itself, will create deviations that plot as a semicircular deviation curve. This is true because the vertical induction changes magnitude and polarity only with magnetic latitude and heel and not with heading of the ship. Therefore, as long as the ship is in the same magnetic latitude, its vertical induced pole swinging about the compass will produce the same effect on the compass as a permanent pole swinging about the compass. Figure 16(a) illustrates the vertical induced poles in the structures of a ship. Generally, this semicircular deviation will be a *B* sine curve, as shown in Figure 16(b), since most ships are symmetrical about the centerline and have their compasses mounted on the centerline. The magnitude of these deviations will change with magnetic latitude changes because the directive force and the ship's vertical induction both change with magnetic latitude.



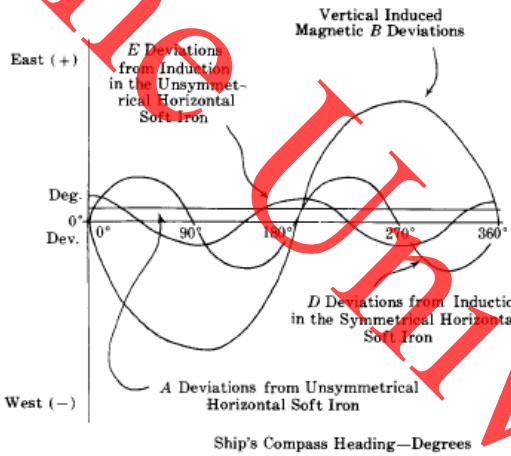


Figure 16(a) Ship's vertical induced magnetism Figure 16(b) Induced magnetic deviation effects

The masses of horizontal soft iron that are subject to induced magnetization create characteristic deviations, as indicated in Figure 16(b). The *D* and *E* deviation curves are called quadrantal curves because they reverse polarity in each of the four quadrants.

Symmetrical arrangements of horizontal soft iron may exist about the compass in any one of the patterns illustrated in Figure 17.

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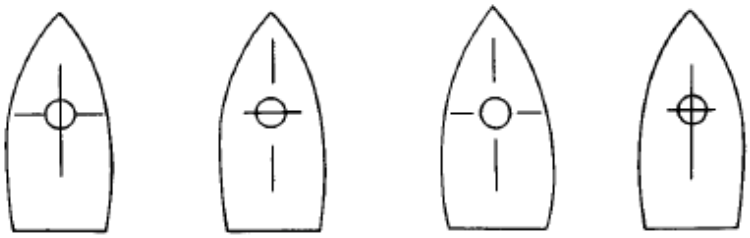

Figure 17 Symmetrical arrangements of horizontal soft iron

The deviation resulting from the earth's field induction of these symmetrical arrangements of horizontal soft iron are illustrated in Figure 18, showing the ship on various compass headings. The other heading effects may be similarly studied.

Such a *D* deviation curve is one of the curves in Figure 15(b). It will be noted that these *D* deviations are maximum on the intercardinal headings and zero on the cardinal headings.

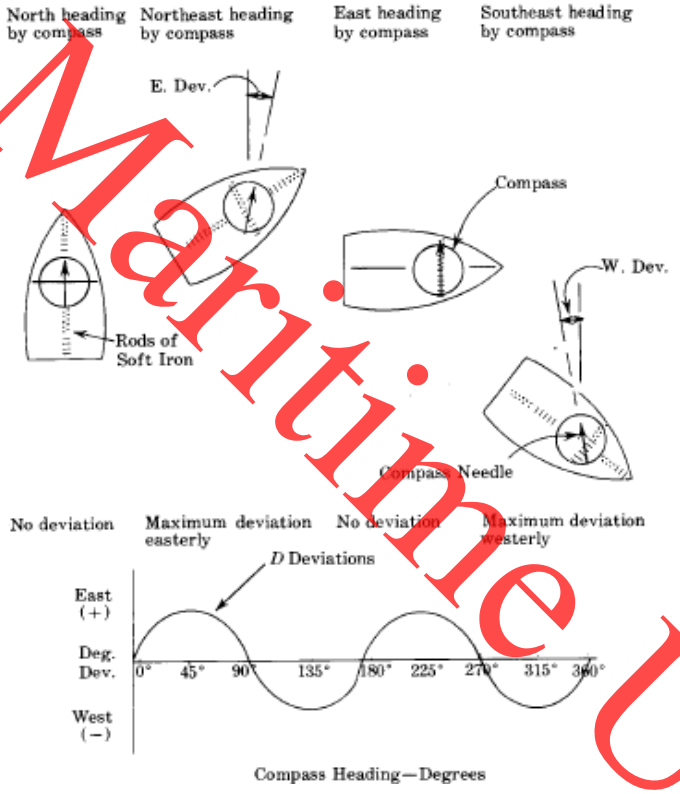

Figure 18 Effects of symmetrical horizontal *D* induced magnetism

Asymmetrical arrangements of horizontal soft iron may exist about the compass in a pattern similar to one of those in Figure 19.

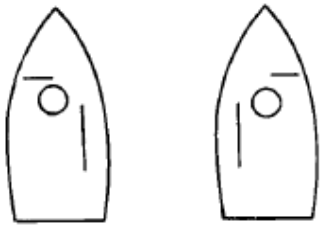

Figure 19 Asymmetrical arrangements of horizontal soft iron

The deviations resulting from the earth's field induction of these asymmetrical arrangements of horizontal soft iron are illustrated in Figure 20, showing the ship on different compass headings. The

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other heading effects may be similarly studied. Such an *E* deviation curve is one of the curves in Figure 15(b). It will be observed that these *E* deviations are maximum on cardinal headings and zero on the intercardinal headings.

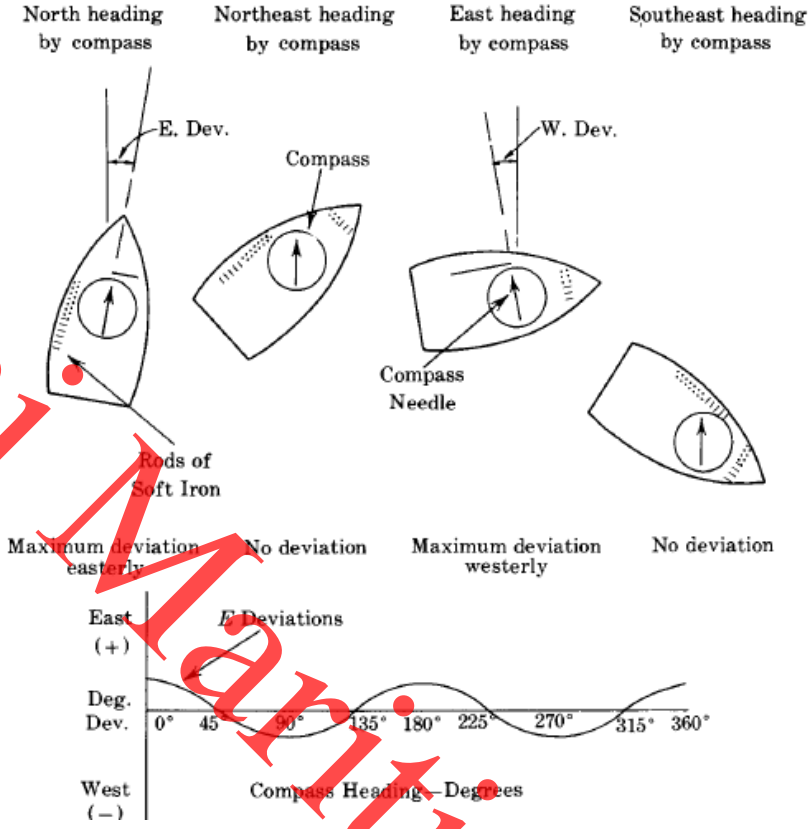

Figure 20 Effects of asymmetrical horizontal *E* induced magnetism

The quadrantal deviations will not vary with latitude changes, because the horizontal induction varies proportionally with the directive force, *H*. The earth's field induction in certain other asymmetrical arrangements of horizontal soft iron creates a constant *A* deviation curve. The magnetic *A* and *E* errors are of smaller magnitude than the other errors, but, when encountered, are generally found together, since they both result from asymmetrical arrangements of horizontal soft iron. In addition to this magnetic *A* error, there are constant *A* deviations resulting from: (1) physical misalignments of the compass, pelorus, or gyro; (2) errors in calculating the sun's azimuth, observing time, or taking bearings.

The nature, magnitude, and polarity of all these induced effects are dependent upon the disposition of metal, the symmetry or asymmetry of the ship, the location of the binnacle, the strength of the earth's magnetic field, and the angle of dip.

Certain heeling errors, in addition to those resulting from permanent magnetism, are created by the presence of both horizontal and vertical soft iron, which experience changing induction as the ship rolls in the earth's magnetic field. This part of the heeling error will naturally change in magnitude with changes of magnetic latitude of the ship. Oscillation effects accompanying roll are maximum on north and south headings, just as with the permanent magnetic heeling errors.

4.3.4 Adjustments and correctors

Since some magnetic effects remain constant for all magnetic latitudes and others vary with changes of magnetic latitude, each individual effect should be corrected independently. Further, it is apparent that the best method of adjustment is to use (1) permanent magnet correctors to create equal and opposite

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vectors of permanent magnetic fields at the compass, and (2) soft iron correctors to assume induced magnetism, the effect of which will be equal and opposite to the induced effects of the ship for all magnetic latitude and heading conditions. The compass binnacle provides for the support of the compass and such correctors. Study of the binnacle in Figure 21 will reveal that such correctors are present in the form of: (1) Vertical permanent heeling magnet in the central vertical tube, (2) Fore-and-aft *B* permanent magnets in their trays, (3) Athwartship *C* permanent magnets in their trays, (4) Vertical soft iron Flinders bar in its external tube, (5) Soft iron spheres.

The heeling magnet is the only corrector that corrects for both permanent and induced effects, and consequently must be readjusted occasionally with radical changes in latitude of the ship. (It must be noted, however, that any movement of the heeling magnet will require readjustment of other correctors.)

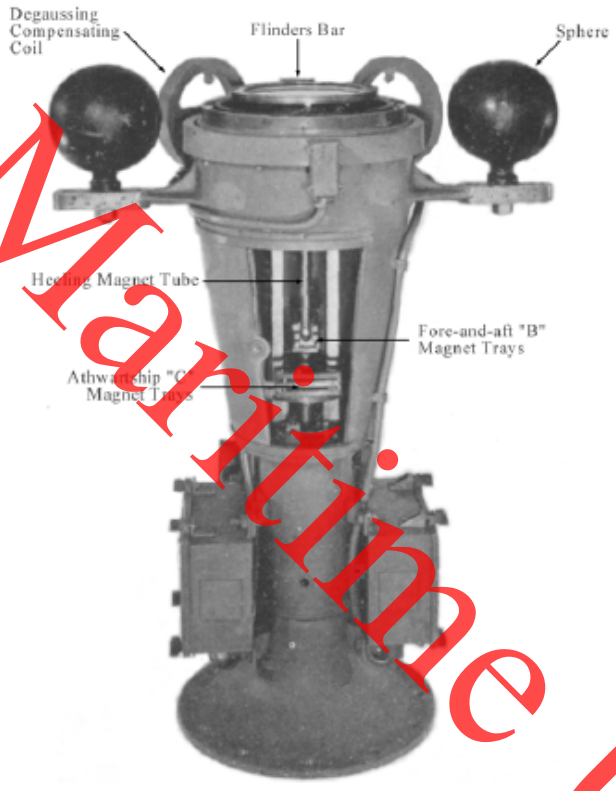

Figure 21Binnacle with compass and correctors

4.3.5 Compass operation

Figure 22 illustrates a point about compass operation. Not only is an uncorrected compass subject to large deviations, but there will be sectors in which the compass may sluggishly turn with the ship and other sectors in which the compass is too unsteady to use. These performances may be appreciated by visualizing a ship with deviations as shown in Figure 22, as it swings from west through north toward east. Throughout this easterly swing the compass deviation is growing more easterly; and, whenever steering in this sector, the compass card sluggishly tries to follow the ship. Similarly, there is an unsteady sector from east through south to west. These sluggish and unsteady conditions are always characterized by the positive and negative slopes in a deviation curve. These conditions may also be associated with the maximum and minimum directive force acting on the compass. It will be observed that the maximum deviation occurs at the point of average directive force and that the zero deviations occur at the points of maximum and minimum directive force.

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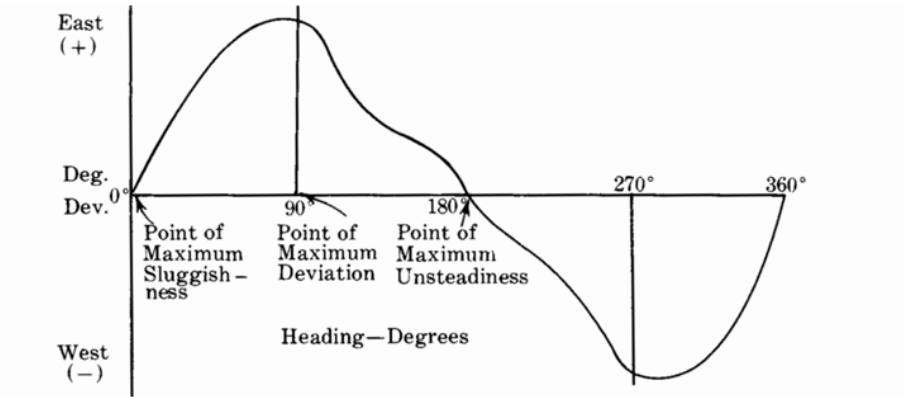

Figure 22 Uncompensated deviation curve

Correction of compass errors is generally achieved by applying correctors so as to reduce the deviations of the compass for all headings of the ship. Correction could be achieved, however, by applying correctors so as to equalize the directive forces across the compass position for all headings of the ship. The deviation method is more generally used because it utilizes the compass itself to indicate results, rather than some additional instrument for measuring the intensity of magnetic fields.

Occasionally, the permanent magnetic effects at the location of the compass are so large that they overcome the earth's directive force, *H*. This condition will not only create sluggish and unsteady sectors, but may even freeze the compass to one reading or to one quadrant, regardless of the heading of the ship. Should the compass be so frozen, the polarity of the magnetism which must be attracting the compass needles is indicated, hence, correction may be effected simply by the application of permanent magnet correctors in suitable quantity to neutralize this magnetism. Whenever such adjustments are made, it would be well to have the ship placed on a heading such that the unfreezing of the compass needles will be immediately evident. For example, a ship whose compass is frozen to a north reading would require fore-and-aft *B* corrector magnets with the red ends forward in order to neutralize the existing blue pole that attracted the compass. If made on an east heading, such an adjustment would be practically complete when the compass card was freed so as to indicate an east heading.

Listed below are several reasons for correcting the errors of the magnetic compass: (1) It is easier to use a magnetic compass if the deviations are small. (2) Although a common belief is that it does not matter what the deviations are, as long as they are known, this is in error inasmuch as conditions of sluggishness and unsteadiness accompany large deviations and consequently make the compass operationally unsatisfactory. This is the result of unequal directive forces on the compass as the ship swings in heading. (3) Furthermore, even though the deviations are known, if they are large they will be subject to appreciable change with heel and latitude changes of the ship.

Subsequent chapters will deal with the methods of bringing a ship to the desired heading, and the methods of isolating deviation effects and of minimizing interaction effects between correctors. Once properly adjusted, the magnetic compass deviations should remain constant until there is some change in the magnetic condition of the vessel resulting from magnetic treatment, shock from gunfire, vibration, repair, or structural changes. Frequently, the movement of nearby guns, doors, gyro repeaters, or cargo affects the compass greatly.

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4.4 Glossary

Magnetism. Any piece of metal on becoming magnetized, that is, acquiring the property of attracting small particles of iron or steel, will assume regions of concentrated magnetism, called poles.

Permanent Magnetism. A bar having permanent magnetism will retain its magnetism when it is removed from the magnetizing field.

Induced Magnetism. A bar having induced magnetism will lose its magnetism when removed from the magnetizing field.

Terrestrial magnetism. The terrestrial magnetism considers the earth as a huge magnet surrounded by lines of magnetic force that connect its two magnetic poles. These magnetic poles are near, but not coincidental, with the geographic poles of the earth.

Ship's heading. Ship's heading is the angle, expressed in degrees clockwise from north, of the ship's fore-and-aft line with respect to the true meridian or the magnetic meridian. When this angle is referred to the true meridian, it is called a true heading. When this angle is referred to the magnetic meridian, it is called a magnetic heading.

Variation. Variation at any place is the angle between the magnetic meridian and the true meridian. If the northerly part of the magnetic meridian lies to the right of the true meridian, the variation is easterly, and if this part is to the left of the true meridian, the variation is westerly.

Deviation. A ship's magnetic influence will generally cause the compass needle to deflect from the magnetic meridian. If the north end of the needle points east of the magnetic meridian, the deviation is easterly; if it points west of the magnetic meridian, the deviation is westerly.

Dip. An angel between the total force of magnetic needles and the horizontal force of theirs.

Soft iron. A kind of iron that is able to produce the induced magnetism under the influence of the terrestrial magnetism.

Hard iron. A kind of iron that is able to produce the permanent magnetism under the influence of the terrestrial magnetism.

Soft sphere. A kind of soft iron installed on the magnetic compass to compensate for deviation produced by one of the induced magnetisms.

Flinder's bar. A kind of soft iron installed on the magnetic compass to compensate for deviation produced by one of the induced magnetisms.

4.5 Revision questions

1 Explain the reasons that the magnetic compass fitted on the steel ships suffers from the deviation.
2 State the relationship between dip, *H* and deviation.
3 Describe the common components of the deviation.
4 State the situations that require the compass shall be swung.
5 Describe the basic deviation correctors installed in the magnetic compass onboard.
6 What kinds of signal flags shall be hoisted when swinging the compass?
7 What is the relationship between true north and magnetic compass north?
8 How to determine the variation?
9 State the difference between the permanent magnetism and the induced magnetism.

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IMO Chapter V of SOLAS Convention

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